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Geometric Variations and Magnetic Field Effects on Electron Energy States and Magnetization of InAs/GaAs Quantum Rings

Yiming Li[1,2], Hsiao-Mei Lu[3], and O. Voskoboynikov[2,4]

[1]National Nano Device Laboratories, Hsinchu 300, Taiwan
P. O. Box 25-178, Hsinchu city, Hsinchu 300, Taiwan
Phone: +886-930-330766 Fax: +886-3-5726639 E-mail: ymli@nctu.edu.tw
[2]National Chiao Tung University, Hsinchu 300, Taiwan; [3]National Tsing Hua University, Hsinchu 300, Taiwan
[4] Kiev Taras Shevchenko University, 64 Volodymirska St., 01033, Kiev, Ukraine

1. Introduction

The semiconductor nanostructures have been of great interests for quantum computing and device applications [1-6]. The fabrication progresses enable us to construct wide range nanoscopic rings [1-3]. The ring shape and size are important elements and affect the electronic structure significantly. Different shapes and sizes have been proposed in studying InAs ring properties. However, the 1D/2D ring models [2,3] for electrons confined by a parabolic potential do not consider ring inner and outer radii effects, the finite hard wall confinement potential, and the non-parabolic band approximation effect for electrons effective mass. The model diversity makes it difficult to compare and verify the results on the basis of experimental results.

In this study we investigate the electron energy states for 3D InAs/GaAs quantum ring with ellipsoidal shape torus (EST) and cut-bottom ellipsoidal shape torus (CBEST). The magnetization [4] of the CBEST nano-ring with different ring radii also has been studied. Contrary to the Aharonov-Bohm periodical oscillation (1D/2D result), we find the penetration of the magnetic field **B** into torus region leads to the magnetization has a non-periodical oscillation. In addition, it is saturated when the applied **B** is increased.

2. A 3D Model and Solution Method

As shown in Fig. 1, we consider rings with the hard-wall confinement potential that is induced by a discontinuity of the conduction band edge of the system [5]. With a given **B**, the electron Hamiltonian is:

$$\hat{H} = \boldsymbol{\Pi}_{\mathrm{r}} \frac{1}{2m(E,\mathbf{r})} \boldsymbol{\Pi}_{\mathrm{r}} + V(\mathbf{r}) + \frac{1}{2} g(E,\mathbf{r}) \mu_B \mathbf{B} \boldsymbol{\sigma}, \qquad (1)$$

where $\boldsymbol{\Pi}_r = -i\hbar \boldsymbol{\nabla}_r + e\boldsymbol{A}(\boldsymbol{r})$ is the electron momentum vector, $\boldsymbol{\nabla}_r$ is the spatial gradient, $\boldsymbol{A}(\boldsymbol{r})$ is the vector potential ($\boldsymbol{B}$ = curl$\boldsymbol{A}$), $\boldsymbol{\sigma}$ is the vector of the Pauli matrixes, and $m(E,\boldsymbol{r})$ and $g(E,\boldsymbol{r})$ are the energy and position dependent electron effective mass. The hard-wall confinement potential in the inner region of the ring (I) and environmental crystal matrix (M) can be presented as: $V(\boldsymbol{r}) = 0$ for all $\boldsymbol{r}$ in I and $V(\boldsymbol{r}) = V_0$ for all $\boldsymbol{r}$ in M. The Ben Daniel-Duke boundary conditions are

$$\Psi_1(\mathbf{r}_s) = \Psi_2(\mathbf{r}_s) \text{ and } \left(\frac{\hbar^2}{2m(E,\mathbf{r})} \nabla_{\mathrm{r}}\right)_{\mathrm{n}} \Psi(\mathbf{r}_s) = const., \qquad (2)$$

where $\boldsymbol{r}_s$ denotes the position of the system interface. The one-electron magnetization $M = -\partial E^N_{tot}/\partial B$, where E^N_{tot} is the summation of all states [4]. We use the nonlinear iterative method to compute energy states and magnetization for the 3D InAs/GaAs rings. This method has been proposed by us for the quantum dots and rings simulation recently [5].

3. Results and Discussion

Figs. 2-4 show the energy states versus inner radius R_{in}, ring radius R, and height z, respectively. The energy states are strongly controlled by the ring size. There are significantly energy differences between EST and CBEST rings. For the CBEST rings with fixed R_{in} and z, Figs. 5 and 6 are the energy states versus **B**. It shows the nonperiodical transition and has good agreement with experiments [2,3,5]. Figs. 7 and 8 are the magnetization of the ring for different R. Contrary to Aharonov-Bohm periodical oscillation (1D/2D result) in meso-scale rings, the magnetization for InAs/GaAs nano-rings has non-periodical and saturated oscillation when **B** is increased. Furthermore, we find the saturation behavior with the smaller R is slow when the **B** is increased.

4. Conclusions

We have proposed a 3D model and solution method for studying the electronic structure of InAs/GaAs nanoscopic rings. We found the electron energy states strongly depend on the ring size and shape. When the **B** is applied, we have observed non-periodical oscillation and effect in the electron energy transition and magnetization for EST and CBEST rings with different sizes. The magnetization has a non-periodical and saturated oscillation. Our study clarified the energy structures and magnetic field effects for nano-rings. It is useful for the applications of spintronics.

Acknowledgments

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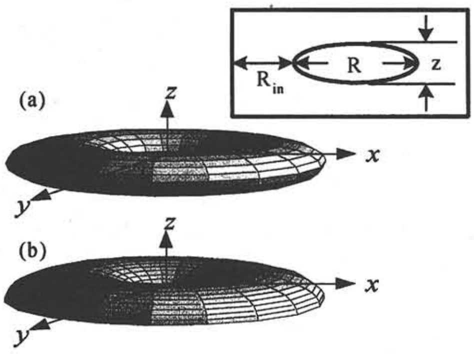

Fig. 1. (a) Ellipsoidal shape torus quantum ring and (b) Cut-bottom ellipsoidal shape torus quantum ring.

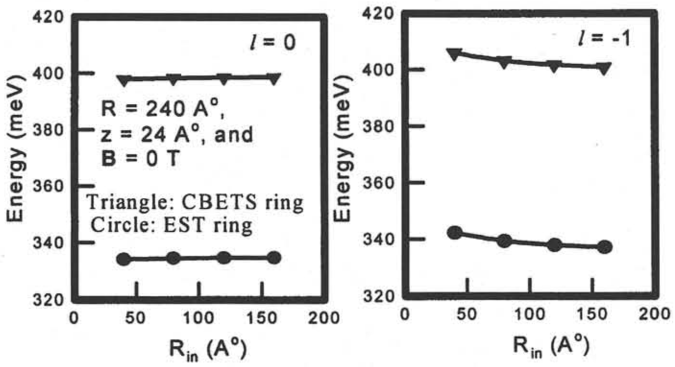

Fig. 2. The electron energy states of InAs/GaAs quantum ring versus the inner radius. The ring height and ring radius are fixed.

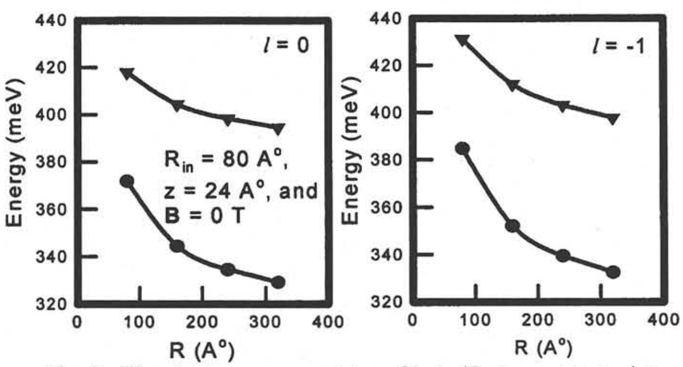

Fig. 3. The electron energy states of InAs/GaAs quantum ring versus the ring radius. The ring height and inner radius are fixed.

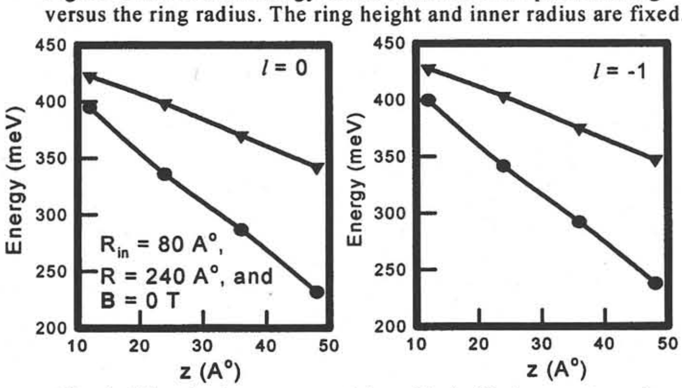

Fig. 4. The electron energy states of InAs/GaAs quantum ring versus the ring height. The ring radius and inner radius are fixed.

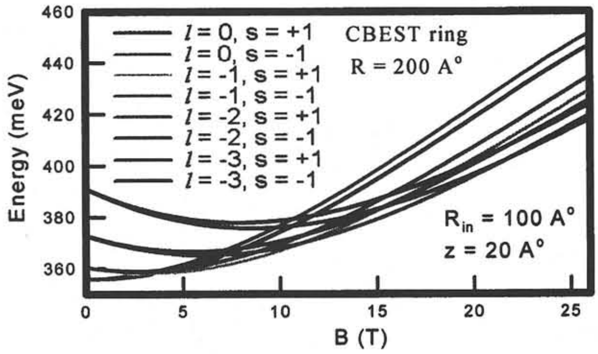

Fig. 5. The electron energy states versus magnetic field. It also shows the energy level spin-splitting.

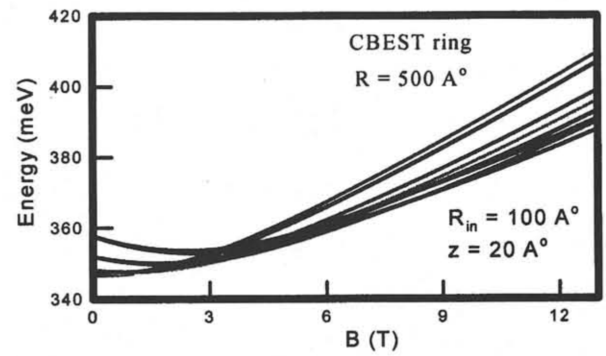

Fig. 6. The electron energy states versus magnetic field. It also shows the energy level spin-splitting.

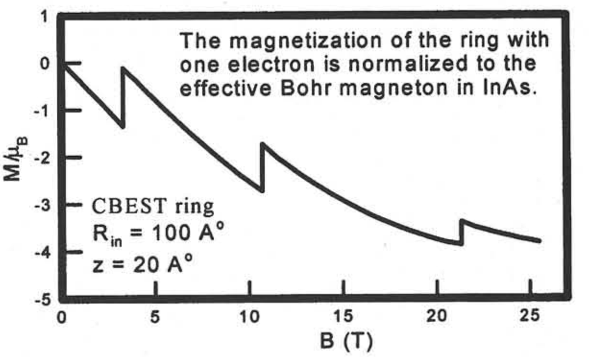

Fig. 7. The magnetization versus the magnetic field of the single electron InAs/GaAs quantum ring with R = 200 A°.

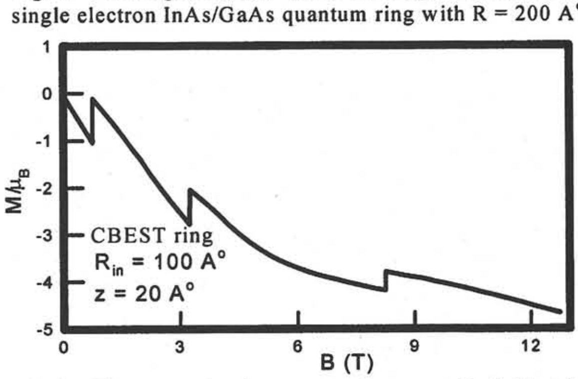

Fig. 8. The magnetization versus the magnetic field of the single electron InAs/GaAs quantum ring with R = 500 A°.