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P h y s i c s

UNIQUE PROPERTIES OF ZnO QUANTUM RINGS

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Electronic states and optical transitions of a ZnO quantum ring containing few interacting electrons in an applied magnetic field are found to be very different from those in a conventional semiconductor system, such as a GaAs ring. Strong Zeeman and Coulomb interactions of the ZnO system, exert a profound influence on the electron states and on the optical properties of the ring. In particular, our results indicate that the Aharonov–Bohm effect in a ZnO quantum ring strongly depends on the electron number.

***Keywords*:** quantum ring, Aharonov–Bohm effect.

Introduction. In a quantum ring structure of nanoscale dimension the confined electrons exhibit topological quantum coherence, famous Aharonov–Bohm (AB) effect [1]. Characteristics of energy spectrum for a ring-shaped geometry, pierced by a magnetic flux Φ, correspond to a periodically shifted parabola with period of one flux quantum, $\Phi_0 = h/e$. All physical properties of this system, most notably, the persistent current [2] and optical transitions [3], have this periodicity. The role of electron-electron interactions on the AB effect was explored systematically for few interacting electrons in a quantum ring [4]. Interactions were found to introduce fractional periodicity of the AB oscillations.

In all these years, for investigations of nanoscale quantum structures such as the quantum dots (QDs) and quantum rings (QRs), the materials of choice had been primarily the conventional semiconductors, viz. the GaAs or InAs heterojunctions. In recent years very exciting developments have taken place with the creation of high-mobility 2DEG in heterostructures involving insulating complex oxides. Unlike in traditional semiconductors, electrons in these systems are strongly correlated [5, 6]. Preparations of various ZnO nanostructures such as nanorings, nanobelts, etc. have been reported in [7].

Theory. Here we report on the AB effect in a ZnO QR and compare that in a conventional semiconductor QR, namely in GaAs. Quite remarkably, we found that while in the non-interacting case the AB effect remains unaltered for both systems, the combination of strong Zeeman interaction and the strong Coulomb interaction, two signature effects of the ZnO 2DEG, make the AB effect disappear in ZnO QR for electron number larger than one. A 2D cylindrical QR with inner radius R_1 and outer radius R_2, containing few electrons, in a magnetic field applied in the growth direction is considered. Then the Hamiltonian of the system is

$$H = \sum_{i}^{N_e} H_{SP}^{i} + \frac{1}{2} \sum_{i \neq j}^{N_e} V_{ij}, \tag{1}$$

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where N_e is the number of electrons in the QR, $V_{ij} = \dfrac{e^2}{\varepsilon}|\mathbf{r}_i - \mathbf{r}_j|$ is the Coulomb interaction term, with dielectric constant of the ring material ε, and $H_{SP} = \dfrac{(\mathbf{p} - e\mathbf{A})^2}{2m} + V_c(r) + E_Z$ is the single-particle Hamiltonian in the presence of an external perpendicular magnetic field, where $\mathbf{A}$ is the vector potential of the magnetic field, m is the electron effective mass. We chose the confinement potential of the QR $V_c(r)$ with infinitely high borders and E_Z is the Zeeman interaction. We take as basis states the eigenfunctions of H_{SP} for $B = 0$ [8]. In order to evaluate the energy spectrum of the many-electron system, we need to diagonalize the matrix of (1) in a basis of the Slater determinants constructed from the single-electron wave functions.

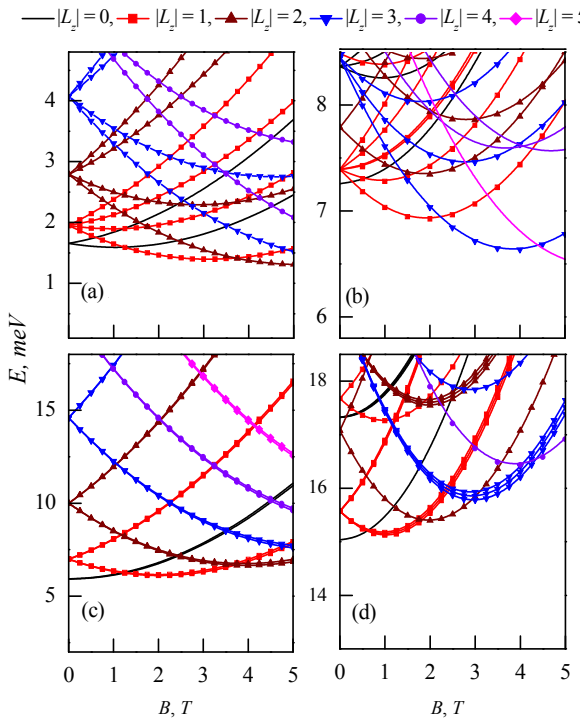

Fig. 1. The low-lying energy levels versus the magnetic field for:
a) ZnO QR with one electron; c) GaAs QR with one electron;
b) ZnO QR with two electrons; d) GaAs QR with two electrons.

We have also considered here the intraband optical transitions in the conduction band. According to the Fermi's golden rule, the intensity of absorption in the dipole approximation is proportional to the square of the matrix element $\langle f| \sum_{j=1}^{N} r_j e^{\pm i\theta} |i\rangle$ when the transition goes from the N-particle initial state $|i\rangle$ to the final state $|f\rangle$. Here r_j and θ_j are the coordinates of j-th electron.

Numerical studies were carried out for the ZnO QR with following parameters: $m = 0.24m_0$, $g = 4.3$, $\varepsilon = 8.5$ (where m_0 is free electron mass). To have a comparison opportunity similar studies for the GaAs QR with parameters $m = 0.067m_0$, $g = -0.44$, $\varepsilon = 13.18$ are presented. The QRs in the both cases are considered to have the same sizes $R_1 = 10\ nm$, $R_2 = 40\ nm$.

The low-lying energy levels of the ZnO QR with one and two electrons for various values of angular momentum L_z are presented in Fig. 1 as a function of the magnetic field B. Similar results are also presented for the GaAs QR in Fig. 1, c and d. In the QR with only one electron in both systems, the ground state changes periodically with increasing magnetic field (Fig. 1, a and c). This is the direct signature of the AB effect in a QR. For the ZnO QR the energy eigenvalues are lower due to the larger value of the electron effective mass. Additionally, the states with different spin are highly split due to the larger value of the g-factor for ZnO.

However, for the non-interacting electrons the AB effect survives in both systems. For QRs with two interacting electrons, there are several substantial differences between the energy spectra of the ZnO and GaAs QRs. For instance, in the GaAs QR we see the usual and well observed AB oscillations due to level crossings between the singlet and triplet ground states, and for each crossing the total angular momentum L changes by unity. On the other hand, for the ZnO QR containing two electrons (Fig. 1, b) the singlet-triplet crossings disappear from the ground state. For small values of the magnetic field the ground state is a singlet with $L_z = 0$ and the total electron spin $S_z = 0$. With an increase of the magnetic field the ground state changes to a triplet with $L_z = -1$ and $S_z = -1$. With further increase of the magnetic field all the observed crossings of the ground state correspond to triplet-triplet transitions between the states with odd number of total angular momentum $(L_z = 1, 3, 5 \ldots)$.

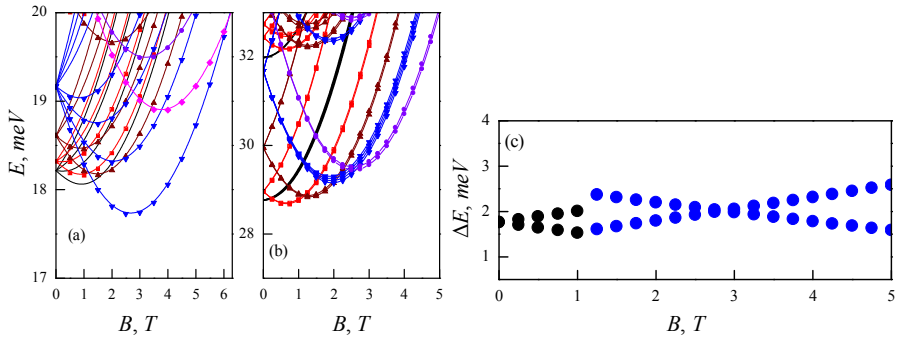

Fig. 2. Same as in Fig. 1., but for: (a) ZnO QR with three electrons; (b) GaAs QR with three electrons; (c) dipole allowed optical transition energies versus the magnetic field for the ZnO QR with 3 electrons.

In Fig. 2, a and b the low-lying energy levels for the ZnO and GaAs QRs containing three electrons are presented as a function of the magnetic field B. For the three-electron GaAs QR we again note the periodic ground state transitions. In contrast to that, for the three-electron ZnO QR only two ground state transitions are visible in that range of the magnetic field. At low magnetic fields the ground state has the angular momentum $L_z = 0$. With the increase of the magnetic field at $B = 1.3\ T$ the ground state changes to $L_z = -3$. The next ground state transition appears at $B = 6\ T$ and the angular momentum changes to $L_z = -5$. Therefore, we can state that in the range of the magnetic field considered here the AB effect disappears. The corresponding optical transition energies for the three-electron ZnO QR are shown in Fig. 2, c, which clearly illustrates the disappearance of the optical AB oscillations in a ZnO QR.

Conclusion. We have studied the electronic states and optical transitions of a ZnO quantum ring containing a few interacting electrons in an applied magnetic field via the exact diagonalization scheme. We have found that the strong Zeeman interaction and the strong electron-electron Coulomb interaction, two major characteristics of the ZnO system, exert a

profound influence on the electron states and as a consequence, on the optical properties of the ring. In particular, we find that the AB effect is strongly electron number dependent.

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REFERENCES

1. **Aharonov Y., Bohm D.** Significance of Electromagnetic Potentials in the Quantum Theory. // Phys. Rev., 1959, v. 115, p. 485–491.
2. **Büttiker M., Imry Y., Landauer R.** Josephson Behavior in Small Normal One-Dimensional Rings. // Phys. Lett. A, 1983, v. 96, p. 365–367.
3. **Halonen V., Pietiläinen P., Chakraborty T.** Optical-Absorption Spectra of Quantum Dots and Rings with a Repulsive Scattering Center. // Euro. Phys. Lett., 1996, v. 33, p. 377–382.
4. **Chakraborty T.** Nanoscopic Quantum Rings: A New Perspective. // Adv. in Solid State Phys., 2003, v. 43, p. 79.
5. **Mannhart J., Schlom D.G.** Oxide Interfaces – An Opportunity for Electronics. // Science, 2010, v. 327, p. 1607.
6. **Hwang H.Y. Iwasa Y., Kawasaki M., Keimer B., Nagaosa N., Tokura Y.** Emergent Phenomena at Oxide Interfaces. // Nat. Mater., 2012, v. 11, p. 103–113.
7. **Lu J.G., Ye Z.Z., Zhang Y.Z., Liang Q.L., Fujita Sz., Wang Z.L.** Self-Assembled ZnO Quantum Dots with Tunable Optical Properties. // Appl. Phys. Lett., 2006, v. 89, id. 023122, p. 3.
8. **Ghazaryan A., Manaselyan A., Chakraborty T.** Tuning of Exciton States in a Magnetic Quantum Ring. // Physica E, 2015, v. 66, p. 157–161.