Impurity-modulated Aharonov–Bohm oscillations and intraband optical absorption in quantum dot–ring nanostructures

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HIGHLIGHTS

• Electron localization inside the structure is fully controllable.
• The ground state is mostly dot-localized due to the presence of the impurity.
• The presence of the impurity and applied magnetic field drastically changes the intraband absorption spectra of the system.

ARTICLE INFO

ABSTRACT

In this work we study the electronic states in quantum dot–ring complex nanostructures with an on-center hydrogenic impurity. The influence of the impurity on Aharonov–Bohm energy spectra oscillations and intraband optical absorption is investigated. It is shown that in the presence of a hydrogenic donor impurity the Aharonov–Bohm oscillations in quantum dot–ring structures become highly tunable. Furthermore, the presence of the impurity drastically changes the intraband absorption spectra due to the strong controllability of the electron localization type.

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1. Introduction

Self-assembled semiconductor quantum nanostructures, such as quantum dots (QDs) and quantum rings (QRs), have been investigated extensively given their potential as building blocks for novel optoelectronic devices, e.g. nanoemitters, and for quantum information technologies [1–4]. The potential of these nanostructures is based on their remarkable similarity to atomic systems. Furthermore, what makes these nanostructures so attractive is the ability to tune their optoelectronic properties by carefully designing their size, composition, strain and shape. These parameters set the confinement potential of the electrons and holes, thus determining the electronic and optical properties of the nanostructure.

It is well known that, due to their geometrical differences with QDs, phenomena observed in QRs are very sensitive to phase coherence of the electronic wave function. An example of such phenomena is the Aharonov–Bohm effect, which consists in the modification of the electron wave function by a vector potential [5] or persistent current [6].

In this paper we focus on a complex nanostructure that combines the two above-mentioned topological components: a QD and a QR. Coupled dot–ring (CDR) nanostructures can be made by pulsed droplet epitaxy [7,8] with full control of the growth process. Due to the unique topology of the CDR structures and their potential applications, the theoretical investigation of CDR's properties has received much attention in recent years. In Ref. [9] a few-electron system confined in a CDR nanostructure in the presence of an external magnetic field was studied by an exact diagonalization technique. It has been shown that the distribution of electrons between the dot and the ring is influenced by the relative strength of the dot–ring confinement and the magnetic field which induces transitions of electrons between the two parts of the system. These transitions are accompanied by changes in the periodicity of the Aharonov–Bohm oscillations in ground-state angular momentum. It has been recently shown [10,11] that many measurable properties of a CDR structure, such as spin relaxation

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or optical absorption, can be significantly changed by modifying confinement potentials, which demonstrates the high controllability and flexibility of these systems. These characteristics are mostly determined by the relative distribution of the wave functions in a CDR that, in turn, can be changed by external gates or fields. Linear and nonlinear optical susceptibilities in a CDR nanostructure have been theoretically studied [12]. In general, it is seen that the structure parameters of the system significantly affects the optical susceptibilities. The enhancement of the coupling effects between the dot and the ring is found to increase considerably the optical susceptibilities. By comparison, linear susceptibilities were found to be more sensitive to structure parameter variation than the nonlinear optical susceptibilities. In Ref. [13] it has been shown that transport properties of CDR nanostructures can be drastically modified due to the unique geometry. Authors have calculated the dc current through a CDR in the Coulomb blockade regime and have shown that it can efficiently work as a single-electron transistor or a current rectifier.

Understanding the impurity states in confined systems is an important problem in semiconductor physics [14]. It is believed that a fundamental study of impurities on semiconducting QR properties under external magnetic fields is important due to the unexpected physical phenomena that may arise from ring-field interaction [6,15–18]. The purpose of this study is to investigate the influence of hydrogenic donor impurity on Aharonov–Bohm oscillations and intraband optical absorption coefficients in CDR nanostructures.

The paper is organized as follows. In Section 2 we describe the theoretical framework. Section 3 is dedicated to the results and discussion, and our conclusions are given in Section 4.

2. Theoretical framework

In our model the electron is confined to a double parabolic potential, where the confining potential of the system consists of two parabolas with various confinement energies, and the system is subjected to a perpendicular magnetic field. The single electron Hamiltonian in a CDR nanostructure in the presence of an on-center hydrogenic donor impurity is given by

$$\widehat{H} = \frac{1}{2m^*}\left(\widehat{\mathbf{p}} - \frac{e}{c}\mathbf{A}\right)^2 + V(\rho) - \frac{e^2}{\epsilon\rho}, \tag{1}$$

where $\widehat{\mathbf{p}}$ is the lateral momentum of the electron, $\mathbf{A} = (-By/2, Bx/2, 0)$ is the vector potential of the external magnetic field with a symmetric gauge, m^* is the electron's effective mass, e is the absolute value of the electron charge and ε is the dielectric constant of the considered material. Here $V(\rho)$ is the confining potential which is given by the following expression [9,12,19–21]:

$$V(\rho) = \min[m^*\omega_d^2\rho^2/2 + V_0, \; m^*\omega_r^2(\rho - R)^2/2], \tag{2}$$

where $\hbar\omega_d$ and $\hbar\omega_r$ are the confinement energies of the dot and ring, V_0 is the depth of the dot confinement with respect to the bottom of the ring potential. The radius of the ring R is defined as the sum of oscillator lengths for the dot and ring related wells and the barrier thickness d between dot and ring according to $R = \sqrt{2\hbar/m^*\omega_d} + \sqrt{2\hbar/m^*\omega_r} + d$. Single electron eigenvalues and eigenfunctions were calculated solving the two-dimensional Schrödinger equation via the exact diagonalization technique [22–24].

The light absorption process can be described as an optical transition that takes place from an initial state to a final one assisted by a photon. The optical absorption calculations for the intraband transitions are based on Fermi's golden rule derived from time-dependent perturbation theory [25–29]:

$$\alpha(\hbar\omega) = \frac{16\pi^2\beta_{FS}\hbar\omega}{n_r V} N_{if}|M_{fi}|^2\delta(E_f - E_i - \hbar\omega), \tag{3}$$

where n_r is the refractive index of the material, V is the volume of the sample per CDR (in this work $V = 64.8 \times 10^{-18}$ cm^3) [8], β_{FS} is the fine structure constant, $\hbar\omega$ is the incident photon energy and E_f and E_i are the energies of the final and initial states, respectively. $N_{if} = N_i - N_f$ is the difference between the number of electrons in the initial and final states. Since we consider a one-particle problem, we assume $N_i = 1$ for the ground state and $N_f = 0$ for all upper states. M_{fi} is the matrix element of the coordinate. The δ-function is substituted by a Lorentzian profile with a full width at half maximum of 0.8 meV.

3. Results and discussion

The calculations are performed for a GaAs/GaAlAs semiconducting system with parameter values $n_r = 3.6$, $m^* = 0.067m_0$, where m_0 is the free-electron mass. Note that in this work we consider only the case of an impurity placed on the center of the CDR structure, i.e. an on-center impurity.

Fig. 1 shows the single electron energies' dependence on magnetic field for different values of the confinement energies and barrier thickness for the case $V_0 = 0$. In all figures the first black line corresponds to the ground state with the following quantum numbers: $(n = 1, l = 0)$, where n is the general quantum number and l is the angular quantum number. Whereas, the second black line corresponds to the state $(n = 2, l = 0)$. It is worth noticing that the influence of magnetic field on the energetic levels essentially depends on the electron's localization type, e.g. dot or ring-type. As it can be seen from figures the ground state energy is almost constant.

This can be explained by the fact that the ground state is dot-localized and the electron is "strongly connected" with the impurity, placed in the center of the structure. In excited states, the electron is localized in both dot and ring regions. For this reason, as seen from figures, the Aharonov–Bohm effect appears, which is typical for ring-like nanosystems. Without a hydrogenic impurity in the CDR structure, the period of the Aharonov–Bohm oscillations has been evaluated by Szafran et al. [9]. The presence of the impurity removes the periodicity of these oscillations because of additional Coulomb interaction. Due to this interaction with the strengthening of magnetic field the ring-localized states (ground and few excited ones) become more dot-localized. That is why the periodicity of the energy level oscillations is absent.

On the other hand, from comparing Fig. 1(a) and (c), it is clear that ground state energy levels increase with rising QD confinement energy. This is due to the increment of the electron's size quantization in the dot region. The exited states are dot–ring-localized due to the tunneling to the ring region, so the average value of the electron–impurity distance increases. For this reason, the energy levels of the corresponding excited states decrease.

For the case of fixed confinement energy values (Fig. 1(a) and (b)) a decrease in the structure's barrier thickness d produces an effective radius decrease. Due to the "strong connection" between electron and impurity, the ground state energy remains almost constant. In excited states, the energy levels of the dot-localized states increase while the ring localized states decrease. This last effect can be understood by the electron–impurity average distance behavior [9].

The single electron energy levels as a function of magnetic field induction for two different values of confinement energies and V_0 are presented in Fig. 2. From Fig. 2(c) it is clear that, for the case with $\hbar\omega_d = 30$ and $\hbar\omega_r = 20$ meV, ground state Aharonov–Bohm oscillations are observed.

For the range of magnetic fields from $B = 0$ up to $B = 4$ T, the following states become the ground level: $(n = 1, l = 0)$, $(n = 1, l = -1)$ and $(n = 1, l = -2)$.
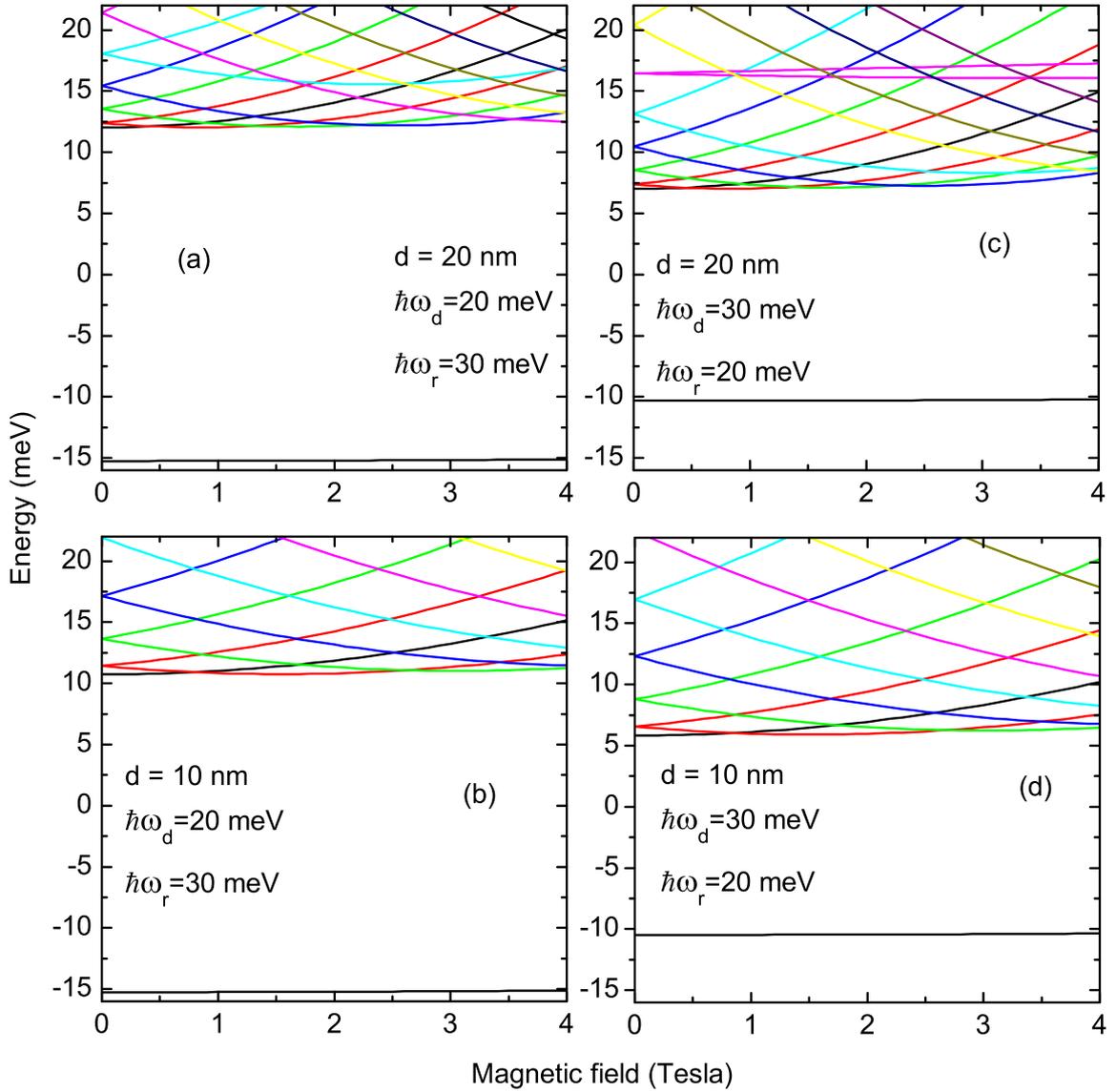
Fig. 1. Energy levels as a function of magnetic field induction. Different values of the confinement energies and barrier thickness have been investigated. The results are for $V_0 = 0$.

This can be explained by the fact that, when $V_0 = 20$ meV the $(n = 1, l = -1)$ and $(n = 1, l = -2)$ states are ring localized and the increment of $\hbar\omega_d$ contributes to the strengthening of the localization in the QR region. As it can be seen from Fig. 2(b) and (d), in the case of $V_0 = -20$ meV, the energy level with quantum numbers $(n = 1, l = 0)$ is almost constant, due to the completely dot localized state. On the other hand, with the increase of $\hbar\omega_d$ the ground state increases because of the strengthening of dot localization. For ring localized states, an increment of $\hbar\omega_d$ leads to a decrease in energy levels. This means that, depending on the geometrical parameters of the CDR structure in the presence of a hydrogenic donor impurity, Aharonov–Bohm oscillations become strongly controllable. This fact will essentially influence the intraband optical properties of the structures.

In order to investigate the intraband optical properties, it is worth to note that in the case of a cylindrical symmetry the intraband optical absorption is allowed for $\Delta l = \pm 1$ transitions.

In our work, the on-center impurity and magnetic field do not destroy the cylindrical symmetry of the system. In Fig. 3 we present the intraband optical absorption coefficient as a function of the incident photon energy for several values of magnetic field induction, confinement energies and barrier thickness of the structure, where we have considered the sum of the absorption coefficients between states $n = 1, 2, 3$. As seen from Fig. 3, the case with $B=0$ leads to the highest intensity maximum of the absorption coefficient, which corresponds to different kinds of transitions: Fig. 3(a) and (b) corresponds to transitions from the $(n = 1, l = 0)$ to the $(n = 2, l = \pm 1)$ state, and Fig. 3(c) and (d) corresponds to transition from the $(n = 1, l = 0)$ to the $(n = 3, l = \pm 1)$ state.

On the other hand, it can be seen that in the case of $B \neq 0$ each peak of the absorption spectra splits into two due to the splitting between states with $l = \pm 1$. In Fig. 3(b) and (d) the contribution of the transition between $(n = 3; l = \pm 1)$ and $(n = 2; l = \pm 1)$ states have also been observed with lower intensities. Note that in all cases if the ground state is dot-localized, the overlap between the initial and final states is largest for the transitions between dot-localized states. With a decrease of d (Fig. 3(a) and (b)) a red shift in the central
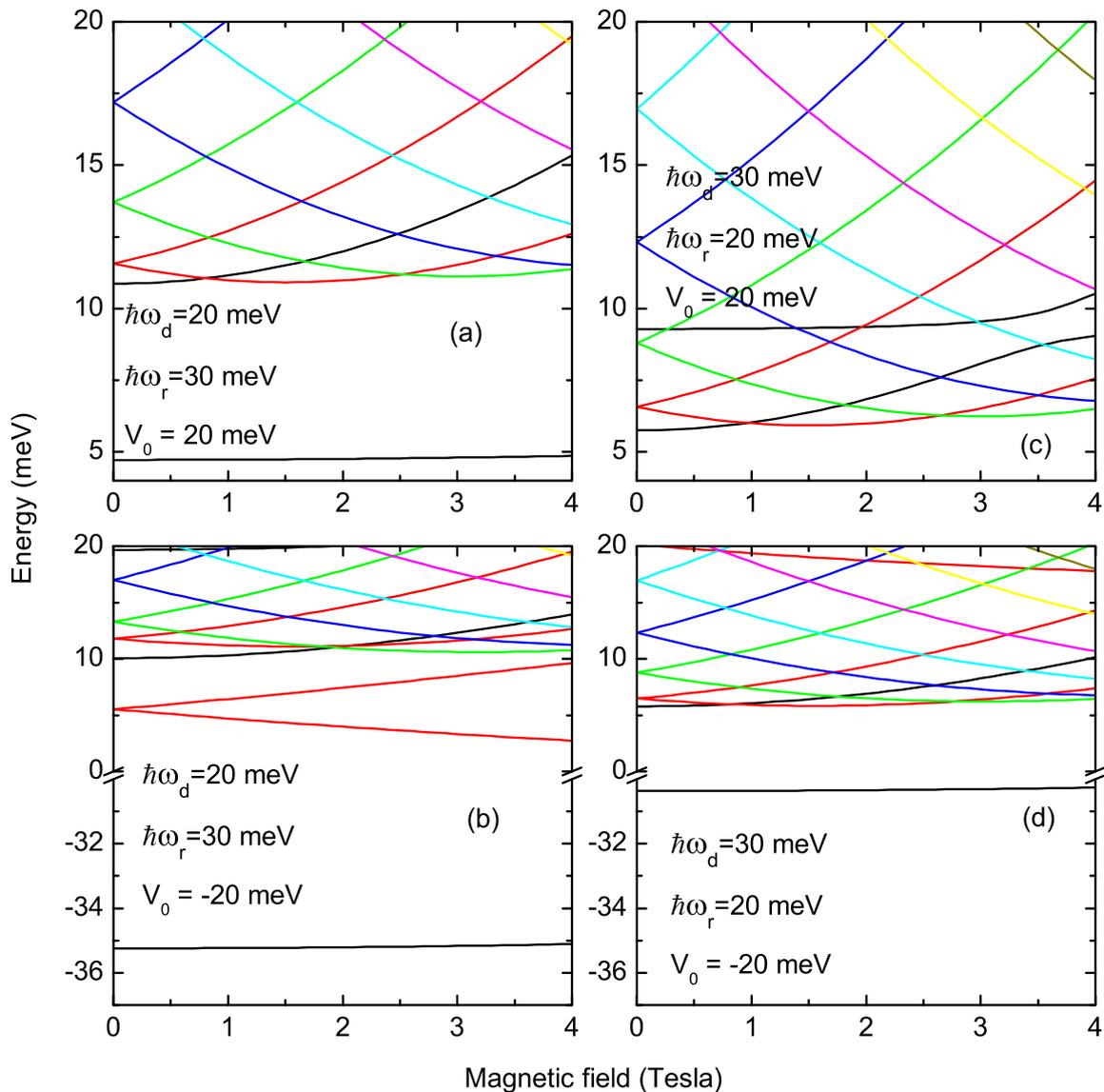
Fig. 2. Energy levels as a function of magnetic field induction. Different values of the confinement energies and depth of the dot confinement with respect to the bottom of the quantum ring potential have been investigated. The results are for $d = 10$ nm.

spectrum has been observed, which is due to the corresponding behavior of the energy distance between the initial and final states. On the other hand for fixed barrier thickness values, and strong quantization of the QD ($\hbar\omega_d = 30$, $\hbar\omega_r = 20$ meV), a blue shift of the absorption spectrum is observed.

In Fig. 4 we present the absorption coefficient as a function of photon energy for various values of confinement energies and V_0. In this case different kinds of transitions appear in the intraband absorption spectrum. In Fig. 4(a), all magnetic field values show transitions to final states ($n = 2; l = \pm 1$) and ($n = 3; l = \pm 1$). In Fig. 4(b) the intensity maximum is highest for the transition from the ground state to the ($n = 1; l = \pm 1$) state, which is the first dot localized excited state. Fig. 4(c) corresponds to the absorption spectrum of a fully ring-like structure (see Fig. 2(c)), therefore the ground state is ring-localized and the transitions are observed between ring-localized states. Due to the Aharonov–Bohm oscil-lations with increasing magnetic field, the overlap between the initial and final states, and therefore the intensity of the absorp-tion coefficient, changes. In Fig. 4(d), like in figures (a) and (b), it is

seen that the absorption spectrum receives a greater contribution from transitions between dot-localized states.

4. Conclusions

We have investigated the influence of on-center hydrogenic donor impurity on Aharonov–Bohm oscillations and intraband optical properties in coupled GaAs quantum dot–ring complex nanostructure. Aharonov–Bohm oscillations in energy spectra have been investigated for various values of structure para-meters. We have shown that electron localization inside the structure is fully controllable, but the ground state is mostly dot-localized due to the presence of the impurity. We have also shown that the presence of the impurity and the applied mag-netic field drastically changes the intraband absorption spectra of the system given the strong controllability of the electron localization type.
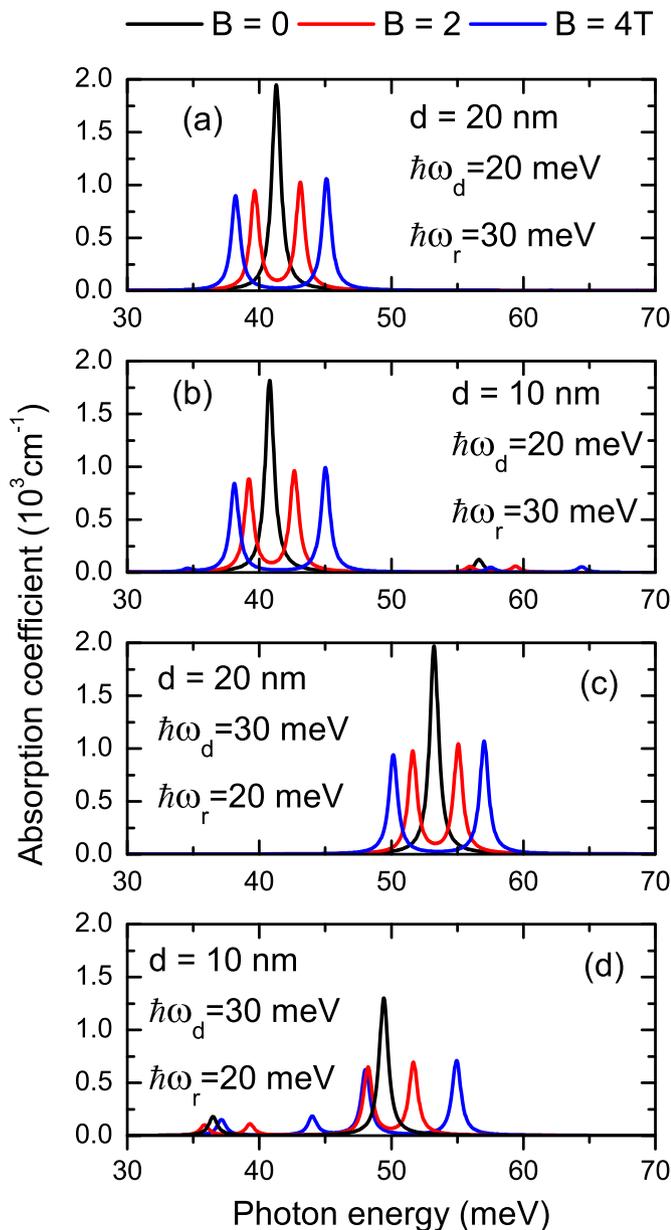
Fig. 3. Dependence of intraband optical absorption coefficient on incident photon energy in CDRs. Different values of the magnetic field induction, confinement energies and barrier thickness have been investigated. The results are for $V_0 = 0$.
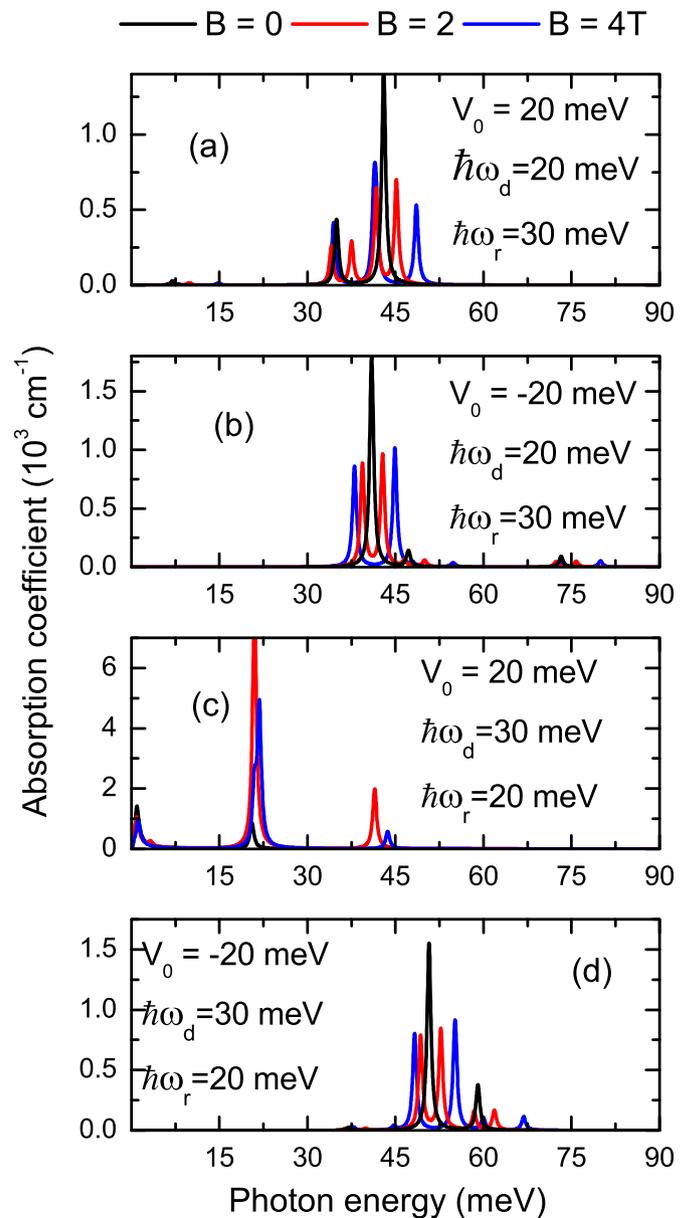
Fig. 4. Dependence of intraband optical absorption coefficient on incident photon energy in CDR. Different values of the magnetic field induction, confinement energies and depth of the dot confinement with respect to the bottom of the quantum ring potential have been investigated. The results are for $d = 10$ nm.

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