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SIMULTANEOUS EFFECTS OF INTENSE LASER AND STATIC ELECTRIC FIELDS ON THE OSCILLATOR STRENGTH IN AN IMPURITY DOPED DISC-LIKE QUANTUM DOT

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The energy levels and oscillator strength of the ground state and first two excited states is calculated in a laser dressed disk-like quantum dot with an on-center hydrogenic donor under applied electric fields. The calculations are performed using the variational method within the effective mass approximation. It is shown that the energy spectrum and probability density of the electron are strongly modified by external perturbations. Our results suggest that the magnitude of the oscillator strength associated with the interlevel transitions is sensitive to the impurity presence, static electric field and the incident laser radiation.

Keywords: oscillator strength, laser dressed quantum dot, hydrogenic donor, electric field.

1. Introduction

The ability to confine spatially the charge carriers in a controlled way in semiconductor heterostructures has led to the observation of new electronic and optical properties in such systems. Among these structures, the most extensively studied is the GaAs/$Al_xGa_{1-x}As$ system because his intrinsec properties are of great interest for technological applications in high-performance electronic and optoelectronic devices [1–4].

Doping semiconductor GaAs QDs allows tuning their electronic and optical properties. This has been proved to be useful for controlling their performance. Therefore, the impurity states in different confining potential shapes have been widely investigated using the traditional techniques such as the perturbation approach [5], the variational methods [6-9], the tight binding self consistent linear screening technique[10], the strong confinement approach [11], or different numerical methods [12-16].

The effects of nonresonant intense laser fields (ILFs) on the confining potential and the corresponding bound states can be also used to control the

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electronic and optical properties of the quantum structures. At frequencies of the order of 1 THz, photon energies are comparable to the energy separation of the electronic levels and nanostructures couple strongly to the electromagnetic field. The laser dressing effects on both the Coulomb impurity potential and the confinement potential in low-dimensional structures have been theoretical investigated [17-20]. It is shown that ILF significantly changes the energy levels and the binding energy of an impurity in these materials with important consequences for their optical properties.

On the other hand, the presence of a static electric field can provide much valuable information about the confined impurities. Experimental and theoretical studies both show that the field induced level shifts (which depend on the location of the impurity in the quantum structure) and a field dependence of the carrier lifetime [21-24].

The intersubband optical absorptions of low-dimensional systems have attracted a great interest in recent years due to the enhanced values of the oscillator strength and a large and easily controlled tunability of transition wavelength [25]. As expected, the strong quantum confinement is an important element for the enhancement of optical transition dipole moments in these systems. Consequently, the intersubband-related linear and nonlinear optical effects in nanostructures have been observed and extensively studied [26-32].

As the parabolic potential is often considered to be a good representation of the potential in semiconductor QDs, the effect of the external perturbations on the dipole transition, the oscillator strength, and the linear and nonlinear optical absorption coefficients in parabolic quantum dots (PQDs) becomes a subject of nowadays interest [33-36]. We also mention reports concerning optical property of a PQD under applied electric fields [37,38], or irradiated by a nonresonant intense laser field [39, 40]

However, to the best of our knowledge, the joint action of an external electric field and an intense laser field on the donor optical response in these structures has so far received little attention. Thus, in order to further understand the phenomena associated with the interlevel transitions modified by the external perturbations in this work we have investigated simultaneous effects of intense laser and electric fields on the oscillator strength in a 2D quantum dot with a parabolic confinement.

The paper is organized as follows. In Section 2 the Hamiltonian and the method used to obtain the dressed energy levels and oscillator strength are described. The analysis of the results for a 2D GaAs QD is presented in Section 3 and the conclusions of our work are reported in Section 4.

2. Theory

2.1. Zero laser field

In the framework of effective mass approximation, an on-center donor impurity in a disc-shaped QD with radius R under applied electric fields can be described by the Hamiltonian:

$$H = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + V(x, y) + eFy - \frac{e_0^2}{\varepsilon_r\, r} \tag{1}$$

where m^* is the electronic effective mass in QD, $e_0^2 = e^2/4\pi\varepsilon_0$ is the reduced electron charge, ε_r effective dielectric constant of the QD material, and $r = \sqrt{x^2 + y^2}$ is the position of the electron. F is the strength of the electric field which is applied along the y-direction.

We model the quantum structure as it is realized in the laboratory [41, 42] by a potential of the form:

$$V(x, y) = \frac{1}{2} m^* \omega_0^2 \left(x^2 + y^2\right) \tag{2}$$

where ω_0 defines the strength of the confinement potential. Usually, the dot radius $R = \sqrt{\hbar / m^* \omega_0}$ is defined as the characteristic length associated with the confining potential [42]

In the absence of the impurity, the envelope wave functions corresponding to the ground and the lowest two excited states are given by:

$$\Phi_{00} = N_0 \exp\left(-\frac{\beta x^2}{2}\right) \exp\left(-\frac{\beta y^2}{2}\right) \tag{3}$$

and

$$\Phi_{0j} = N_j \exp\left(-\frac{\beta x^2}{2}\right) \exp\left(-\frac{\beta\left(y + F/2\beta^2\right)^2}{2}\right) H_j\left(\sqrt{\beta}\left(y + F/2\beta^2\right)\right) \tag{4}$$

where j = 1,2 and N_j is the normalization constant. $\beta = m^* \omega_0 / \hbar$ and H_j is the Hermite polynomial.

In order to obtain the impurity eigenfunctions for the GaAs QD, we adopted a variational scheme. The corresponding trial wave functions are chosen as [43]:

$$\Psi_{n_x n_y}(x, y, \lambda) = \Phi_{n_x n_y}(x, y) \exp(-\lambda r) \tag{5}$$

where λ is the variational parameter. The donor energies are determined by means of

$$E_{n_x n_y} = \min_{\lambda} \frac{\left\langle \Psi_{n_x n_y}(x,y,\lambda) \middle| H \middle| \Psi_{n_x n_y}(x,y,\lambda) \right\rangle}{\left\langle \Psi_{n_x n_y}(x,y,\lambda) \middle| \Psi_{n_x n_y}(x,y,\lambda) \right\rangle}. \tag{6}$$

2.2. Laser-dressed potentials

Under a non-resonant intense laser field with the polarization direction parallel to the *y*-axis, in the high-frequency limit [44,45] the electron "sees" a laser-dressed confinement potential which is obtained by averaging the potential $V(x, y+\alpha(t))$ over a period:

$$\tilde{V}(x,y,\alpha_0) = \frac{\omega}{2\pi} \int_0^{2\pi/\omega} V(x, y+\alpha(t))\,dt \tag{7}$$

The quantity:

$$\alpha(t) = \alpha_0 \sin(\omega t) \tag{8}$$

describes the motion of the electron in the laser field. α_0 is the laser-dressing parameter [44] defined as:

$$\alpha_0 = \frac{e A_0}{m^* \omega} \tag{9}$$

where ω and A_0 are the frequency and vector potential amplitude of the laser field, respectively. Within the high-frequency field approach, the dressed parabolic confinement potential becomes:

$$\tilde{V}_{conf}(x,y,\alpha_0) = m^* \omega_0^2 \left(x^2 + y^2 + \alpha_0^2/2\right) \tag{10}$$

For the Coulomb potential, $V_C = -\frac{e_0^2}{\varepsilon_r r}$, in the strong laser field limit Lima and Miranda [46] suggest the replacement of the singularity in this term by a soft-core potential

$$\tilde{V}_C = -\frac{e_0^2}{\varepsilon \sqrt{r^2 + \alpha_0^2}}. \tag{11}$$

The same approximation for the impurity potential has been used by Safarpour et al. [47] in the study of the optical properties for a spherical laser dressed QD confined in a cylindrical nanowire.

The laser dressed energies of the donor impurity are obtained by minimizing the energy functional

$$\frac{\left\langle \Psi_{n_x n_y}(x,y,\lambda) \middle| \tilde{H} \middle| \Psi_{n_x n_y}(x,y,\lambda) \right\rangle}{\left\langle \Psi_{n_x n_y}(x,y,\lambda) \middle| \Psi_{n_x n_y}(x,y,\lambda) \right\rangle} \tag{12}$$

where:

$$\tilde{H} = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)+\tilde{V}(x,y,\alpha_0)+eFy+\tilde{V}_C(r,\alpha_0) \tag{13}$$

is the Hamiltonian of the 'laser-dressed' hydrogenic donor in a GaAs QD.

We assume now that the QD system is under the action of a near resonant light field polarized in y-direction which induces a transition between the initial state E_i and the final state E_f. A very important physical quantity in the study of the optical properties related to the electronic dipole-allowed transitions is the oscillator strength. This dimensionless quantity is defined as [48]

$$P_{fi} = \frac{2m^*}{\hbar^2}\Delta E_{fi} M_{fi}^2 \tag{14}$$

where $\Delta E_{fi} = E_f - E_i$ and $M_{fi} = \left\langle \Psi_f \middle| y \middle| \Psi_i \right\rangle$ is the dipole transition matrix element. The oscillator strength describes the strength of absorption lines and it offer additional information on the fine structure and selection rules of the optical absorption. For impurities located at the dot center and y-polarized pump radiation the allowed transitions is for $\Delta n_y = \pm 1$. We are going to calculate the oscillator strengths of intraband transitions from Ψ_{01} state to Ψ_{00} and Ψ_{02}-states.

3. Results and discussion

In this study the numerical calculations for an on-center donor impurity in a GaAs disk-like QD with parabolic confinement are presented. The parameters used in our calculations are [13]: m^* = 0.0665m_0 (where m_0 is the free electron effective mass), the static relative dielectric constant $\varepsilon_r = 12.58$ and the dot radius $R = 5nm$.

In Figs. 1(a)-3(a) the energy levels of the first three dressed states of the impurity are plotted as functions of the electric field strength for several values of the laser intensity: α_0 =0, 1, 2, 3, 4 and 5 nm. For the electric field range studied we observe that the donor energies decrease quadratically with F, irrespective of the laser parameter. A similar dependence of the Stark shift $\Delta E = E(F) - E(F=0) = -\beta F^2$ has been obtained for a cylindrical shaped self-assembled GaAs/AlGaAs under a tilted electric field without an applied laser field

[49]. For the studied donor states it is observed that the impurity polarizability β is less affected by the light irradiation.

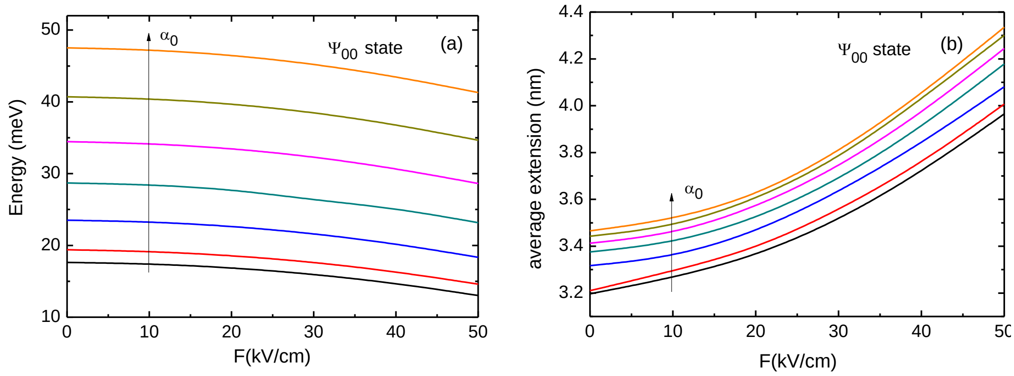

Fig. 1. (a) Energy of the ground state and (b) the expectation value of the distance along the field-direction between the electron and the dressed Coulomb center as a function of the electric field strength for on-center impurity in a GaAs disk-like quantum dot. The results are for several values of the laser parameter. α_0 =0 (black); 1nm (red); 2 nm (blue); 3 nm (dark olive); 4 nm (magenta); 5 nm (dark yellow) and 6 nm (orange), respectivelly.

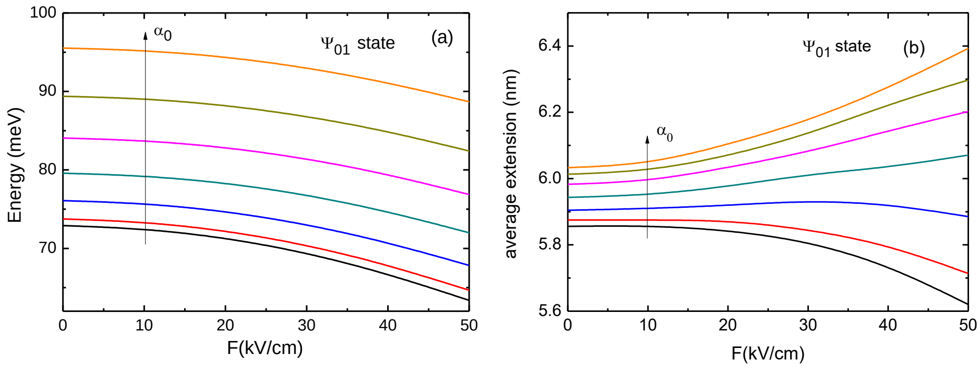

Fig. 2. As in Fig. 1, for the first excited states

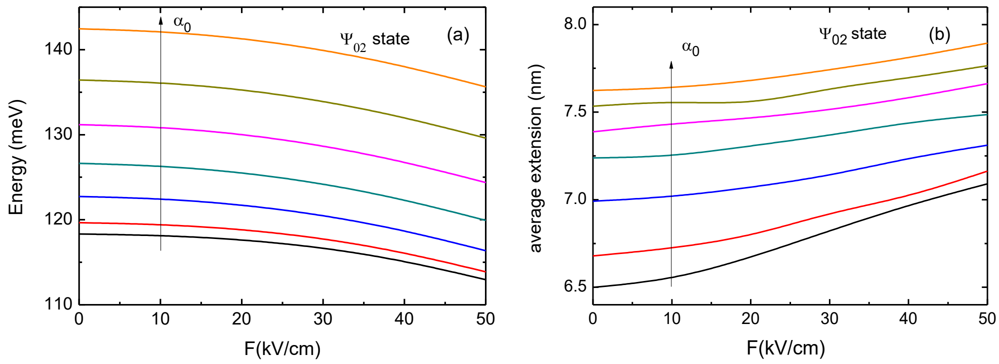

Fig. 3. As in Fig. 1, for the second excited states

As expected, the energy levels are growing functions with the magnitude of α_0. This laser field induced blue shift has been widely reported in the literature [34,35] and it is essentially due to the displacement of the potential bottom towards higher energy values.

Figs. 1(b)-3(b) show the expectation values of the distance between the electron and the Coulomb center along the electric field direction, $\sqrt{\langle y^2 \rangle}$, as functions of the electric field strength for several values of the laser intensity. The figures indicate that the laser field has a more pronounced influence on the first excited state of the impurity (Fig. 2(b)). The average extension in this case decreases with F for small α_0 values, α_0 < 3 nm, and increases for higher laser intensity. This is in contrast to the Ψ_{00} and Ψ_{02} states behavior where the increment induced by the electric field is maintained even for small values of α_0. One notices also the rise of the spatial extension for all studied impurity states with the increase of the laser parameter, more pronounced for the second excited state. Due to larger spatial extensions, Ψ_{02} wave function is more sensitive to the influence of the electric field and it becomes more polarized.

The behavior of the average extension may be understood in terms of the electron cloud localization in the nanostructure. This localization may be modified by simultaneous influence of electric field and laser radiation. These features are presented in Fig. 5, which displays the contour plots of the probability density for the first three dressed states of the impurity in a disk-like GaAs QD for different values of the applied electric field and laser parameter. In each of the rows we plot the impurity states for $\alpha_0 = 1$ nm (Fig. 5(a)) and $\alpha_0 = 5$ nm (Fig. 5(b)), respectively.

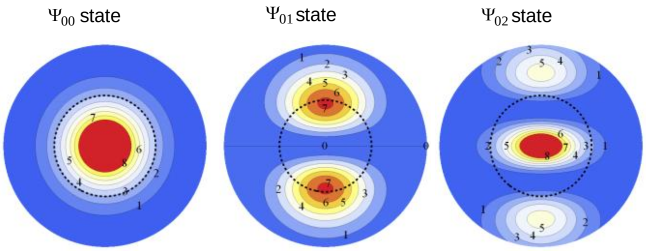

Fig. 4. Contour plot of the probability density for the first three dressed states of the impurity in the disk-like QD without external perturbations ($\alpha_0 = 0;$ F=0).

For comparison in Fig. 4 same quantities are plotted for a structure without external perturbations ($\alpha_0 = 0;$ F=0).

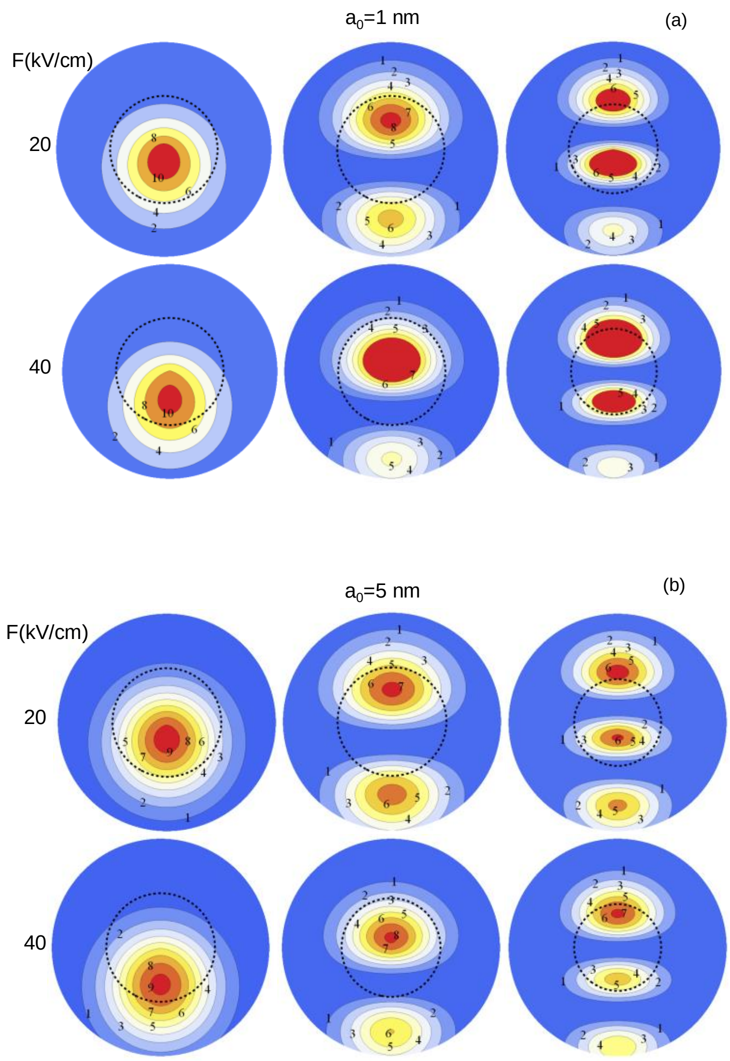

Fig. 5. The probability density for the ground state (left column) first (midle column) and second (right column) excited states of an on-center impurity in a GaAs QD. Results are for $\alpha_0 = 1$ nm (a) and $\alpha_0 = 5$nm (b) and two values of the applied electric field.

As Figure 5 shows, while the probability density of the ground state displaces in the opposite direction of the electric field, the electron cloud of the first excited state $|\Psi_{01}|^2$ shifts along the field direction. A similar "anomalous polarization" effect of the excited states was reported for square quantum wells

[50], parabolic two-dimensional quantum rings [34] and double QDs [32] under applied electric fields.

This effect relates with the competition between the electrostatic force upon the electron and maintaining of the orthogonality condition between states [34]. Thus, Ψ_{01} is displaced in the direction of the field because Ψ_{00} shifts in the opposite direction, so that $\langle \Psi_{01} | \Psi_{00} \rangle = 0$. Again, for the second excited state in the electric field presence the behavior of the electron cloud is a result of the competition between the electrostatic interaction and keeping of the orthogonality condition between states.

Note that in the laser field presence the impurity states are less confined due to the spreading of the electron wave functions and a diminishing of the Coulomb interaction. For small laser intensities with the increase of the electric field the main peak of the probability density for Ψ_{01} state is shifted toward the impurity center (see Fig. 5(a)). Consequently, up to $\alpha_{0c} \cong 3$ nm the average distance between the electron and the dressed Coulomb center decreases. For further large laser intensities, the Coulomb term is weakened and both maxima of the Ψ_{01} wave function are pushed away from the impurity under electric field action. So, in agreement with the results plotted in Fig. 2b, a significantly enlarged electron-impurity distance induced by the electric field occurs for high values of the laser intensity.

The oscillator strength given by Eq. (14) depends on the transition energy $\Delta E_{fi} = E_f - E_i$ and the transition matrix element related to the coordinate *y*. Figs. 6 and 7 show dependence of these quantities on the laser dressing parameter for different electric field strengths. From Fig. 6(a) it is possible to notice that the $0 \rightarrow 1$ transition energy is a decreasing function of F for any α_0 value. One more interesting behavior exhibits the $1 \rightarrow 2$ transition energy. It shows an obvious blue shift for $\alpha_0 \leq \alpha_{0c}$ in the low electric field regime. Then, as we consider more intense electric fields of 40 and 50 kV/cm, ΔE_{21} reduces by growing the laser field intensity. On the other hand, for large α_0 values the effect of the external electric field on the $1 \rightarrow 2$ transition energy becomes negligible. This can be seen from the behavior of the curves in Fig. 7a, which for $\alpha_0 > 4$ nm almost coincide for different values of the electric field *F*.

The calculated values of the transition matrix element shown in Figs. 6(b) and 7(b) give a global indication of the external perturbations effect on the spatial overlapping between the involved wave functions. We observed that the laser dressing causes an increase of the transition matrix element in the whole range of the electric fields here considered. This is because the electron is more delocalized as the laser parameter increases, so that the dressed WFs spread over whole structure and their superposition becomes important. Instead, as long as the electric field strengthens the maximum of the Ψ_{01} wave function is displaced farther than the corresponding to lower state (in the $0 \rightarrow 1$ transition) or upper state ((in the $1 \rightarrow 2$ transition). Therefore they will have a lesser degree of overlap leading to a reduction in their matrix element.

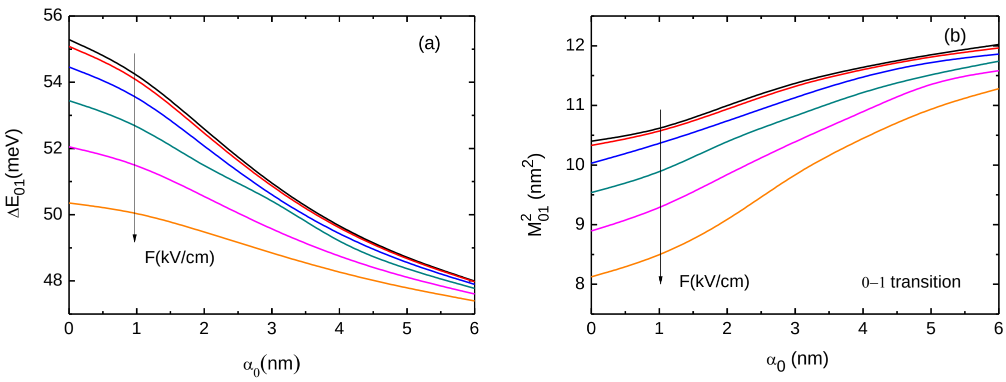

Fig. 6. $0 \rightarrow 1$ transition energy (a) and the coresponding matrix elements (b) for an on-center impurity in a GaAs QD as functions of the laser field parameter for several electric field strengths: $F = 0$ (black), 10 kV/cm (red), 20 kV/cm (blue), 30 kV/cm (dark olive), 40 kV/cm (magenta) and 50 kV/cm (orange), respectively.

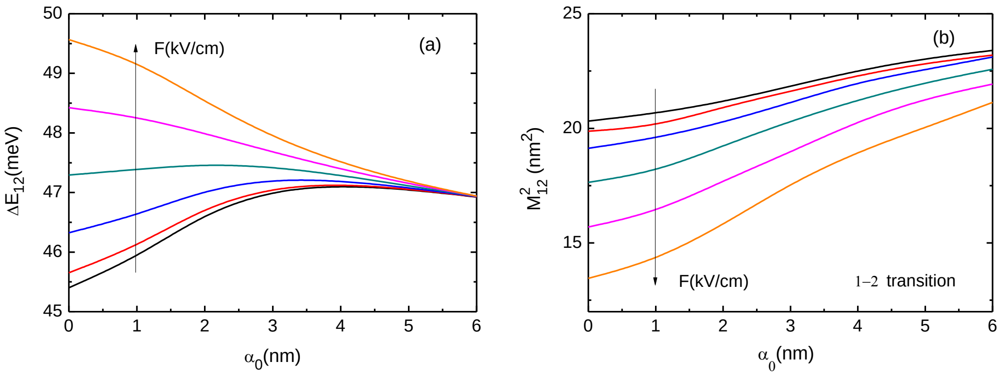

Fig. 7. As in Fig.6, for the $1 \rightarrow 2$ interlevel transition.

Fig. 8 presents the oscillator strength for $0 \rightarrow 1$ (Fig. 8a) and $1 \rightarrow 2$ (Fig. 8b) transitions as a function of laser parameter for several applied electric strengths. By comparing Fig. 8a with 6b (or Fig. 8b with 7b) it is observed that M_{fi}^2 is the dominant term in the whole range of the α_0-values considered.

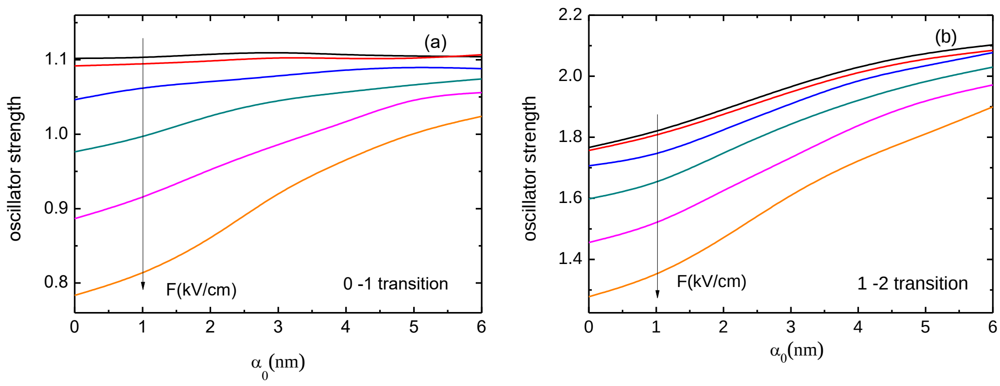

Fig. 8. The variations of oscillator strength as a function of laser field parameter for different the electric field strength (a) $0 \to 1$ interlevel transition; (b) $1 \to 2$ interlevel transition.

One can notice:

(i) large values of the oscillator strength due to the quantum confinement effect and

(ii) an increase of this quantity for transitions between levels with higher energy caused by enhancement of the corresponding matrix elements (see Figs. 6b and 7b).

These features explain the high efficiency of photoluminescence and large optical nonlinearities associated with interlevels optical absorptions in the quantum dots.

4. Conclusions

The energy levels and the oscillator strength associated with interlevel transitions in an impurity doped disc-like quantum dot under electric and intense laser fields are calculated using the variational method and effective mass approximation. We found that the external perturbations strongly influence the energy levels of the electronic states, their localization in the dot and consequently matrix elements of the dipole moments. Large values of the oscillator strength due to the quantum confinement effect are predicted. We expect that these results will be useful for experimental works focused on new optoelectronic devices.

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