Journal of Interfaces, Thin films, and Low dimensional systems 3 (1) Summer and Autumn (2019) 233-243

Simultaneous effects of optical intensity and magnetic field on optical properties of GaN/AlN multi-wells quantum rings with constant outer radius

Scientific research paper

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ARTICLE INFO

Article history:
Received 19 August 2020
Revised 5 October 2020
Accepted 5 October 2020
Available online 15 October 2020

Keywords:
Fixed radius multi-wells quantum rings
Optical absorption coefficients
Optical intensity
Magnetic field

ABSTRACT

Here, we study the effect of the optical intensity, external magnetic field, well number and quantum ring thicknesses on the optical absorption of AlN/GaN constant radius multi-wells quantum rings. We show that when the intensity increases, the total absorption coefficient reduces. This fact is independent of the inner quantum ring radius R_{in}, magnetic field, and number of wells. The total absorption coefficient reduces monotonically when the number of wells increases. However, the system with R_{in}=400 Å at zero magnetic field is an exception. In this system, if the number of wells increases, the total absorption coefficient firstly decreases and then increases. By increasing R_{in}, the total absorption coefficient monotonically reduces. This monotonic decreasing behavior exists for systems with more number of wells and higher magnetic fields. At fixed R_{in} and for systems with greater number of wells and higher values R_{in}, the total absorption coefficient monotonically decreases when the magnetic field increases. Finally, at lower magnetic fields, the total absorption coefficient decreases more rapidly than in higher magnetic fields.

1 Introduction

Experimental techniques in manufacturing few electron quantum rings [1] and dots [2] have made quantum rings an interesting experimental research topic that can provide a new field of study for the many-body theory in quasi-one-dimensional systems. Observation of the persistent current [3] and Aharonov–Bohm oscillations [4] in small rings has also increased this interest. Hereby, single-electron theory can explain many properties of quantum rings which are assumed as a one-dimensional system.

Analysis of photon-semiconductor interactions form a quantum mechanical point of view provides us a theory [5] with which the intersubband absorption coefficients can be obtained. By using this pioneer work, influences of different effects on the absorption coefficient of a wide range of quantum confining systems have been studied till now. In this area, for example, the effects of magnetic [6] and electric fields [7], incident optical intensity [8], and different shapes of the confining potential such as hyperbolic [9], delta-doped [10], and triangular [11] ones, have been explored. However, the intensity effects on the optical properties on GaN/AlN multi-wells quantum rings with constant effective radius at different magnetic field values have not been yet studied.

In the last decade, III–V nitride semiconductors were extensively investigated, where GaN (a direct wide band-gap semiconductor) alloyed with InN and AlN,

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DOI: 10.22051/jitl.2020.32747.1044

covers a spectrum from visible to ultraviolet [12-13]. Applications of GaN and AlN for violet, blue, and green light emitting devices and high temperature transistors are just because of their wide band gaps and strong bond strengths [14]. Experimental fabrication of AlN/GaN multi-quantum wells by using RF plasma-assisted molecular beam epitaxy [15] have previously been performed. Besides, experimental [15-16] and theoretical [17] study of intersubband absorptions of these structures with variable total length have also been studied.

During the last few years, the effects of different parameters on the optical absorption properties of semiconducting nanostructures such as Dielectric environment effect [28], Rashba spin-orbit interactions [37], impurity [29], fractal shaped nanostructures [39], electric field [30], core/shell potential [31-32], two-electron [33], three electrons [35], intense laser field effects [40], electron–electron interactions [38], electron–phonon interaction [34], energy-dependent effective mass [36], hydrostatic pressure and temperature [41], position-dependent effective mass [42], and n-type double δ-doped systems [43], have been explored.

In our previous studies [18-19], we considered optical absorption properties of constant total effective length multiple quantum wells (CTEL-MQWs) for different semiconducting systems such as III-V semiconductors, GaAs/AlGaAs [18] in addition to AlN/GaN [19] multi-quantum wells. Recently, we have considered the optical absorption properties of constant total effective radius multi-wells quantum rings (CTER-MWQRs) [20] and GaN/AlN two electron constant total effective radius multi-shells quantum rings (2e-CTER-MSQRs) [21].

In this paper, we have considered the effects of the intensity, magnetic field, well number, and quantum ring radius on the absorption coefficient of GaN/AlN constant outer radius multi-wells quantum rings (COR-MWQRs).

2 Formalism

Here, we use the radial Schrödinger equation in the cylindrical framework. We use the envelope-function technique as well as effective mass approximation to study a quantum ring with the threading uniform magnetic field B perpendicular to the ring plane:

$$-\frac{\hbar^2}{2}\frac{\partial}{\partial\rho}\left(\frac{1}{m^*}\frac{\partial R_{n,l}}{\partial\rho}\right)-\frac{\hbar^2}{2m^*}\frac{1}{\rho}\frac{\partial R_{n,l}}{\partial\rho}+\frac{\hbar^2}{2m^*}\frac{m^2}{\rho}R_{n,l}+\frac{1}{2}m\hbar\omega_c R_{n,l}+\frac{1}{8}m^*\omega_c^2\rho^2 R_{n,l}+V(\rho)R_{n,l}=ER_{n,l}, \quad (1)$$

where $m = 0, \pm1, \pm2, \ldots$ is the magnetic quantum number, m* is the effective mass, and $\omega_c = eB/m^*$ is the cyclotron frequency. Now, we define the geometrical potential $V(\rho)$ as:

$$V(\rho)=\begin{cases}V_{conf} & i=1,3,\ldots\\ 0 & i=2,4,\ldots\end{cases};\ \frac{i-1}{2N+1}R_{in}<\rho<\frac{i}{2N+1}R_{out}, \quad (2)$$

where, N, l, and V_{conf} are the number of wells, orbital quantum number, and relative conduction band offset, respectively. The parameter i indicates the i'th well or barrier. R_{in} and R_{out} show the inner and outer quantum ring radii, respectively. Figure 1 shows an illustration of multiple quantum wells in a quantum ring. After evaluation of the eigen-energies and eigen-function by using the finite difference method [22,44], the linear absorption coefficient associated with the (E_f–E_i) transition can readily be computed [23]

$$\alpha^{(1)}(\omega)=\omega\sqrt{\frac{\mu}{\varepsilon_r}}\times\frac{\sigma_s e^2|M_{fi}|^2\hbar\Gamma_{fi}}{(\hbar\omega-\Delta E_{fi})^2+(\hbar\Gamma_{fi})^2} \quad (3)$$

Also, the third-order nonlinear optical absorption coefficient for the mentioned intersubband transition is [24]

$$\alpha^{(3)}(\omega)=-\omega\sqrt{\frac{\mu}{\varepsilon_r}}\times\left(\frac{I}{2\varepsilon_0 n_r c}\right)\frac{\sigma_s e^4|M_{fi}|^2\hbar\Gamma_{fi}}{\left[(\hbar\omega-\Delta E_{fi})^2+(\hbar\Gamma_{fi})^2\right]^2}\times\left[4|M_{fi}|^2-\frac{|M_{ff}-M_{ii}|^2\left[3\Delta E_{fi}^2-4\Delta E_{fi}\hbar\omega+\hbar^2(\omega^2-\Gamma_{fi}^2)\right]}{\Delta E_{fi}^2+(\hbar\Gamma_{fi})^2}\right], \quad (4)$$

where I, ω, and σ_s are the optical intensity, incident wave angular frequency, and electron density.

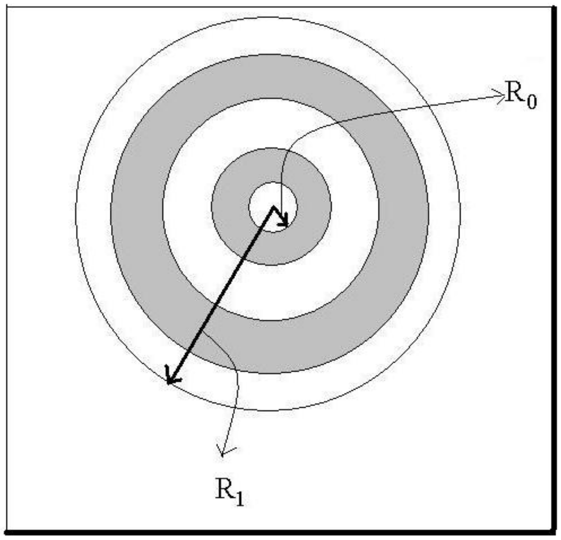


Figure 1, An illustration of multiple quantum wells in a quantum ring.

M_{fi} is the dipole matrix element which can be defined as [45], $M_{fi} = \int R^{f}_{n,l} \left|e\rho^3\right| R^{i}_{n,l} d\rho$. Also, E_i and E_f show the initial and final energy levels. The parameters μ , c, and n_r are the permeability free space light speed, and refractive index. Besides, $\Gamma_{fi}(f \neq i)$ denotes the inverse of relaxation time T_{fi} (=1.5 ps [25]) for states $|f\rangle$ and $|i\rangle$, i.e. $\Gamma_{fi} = 1/T_{fi}$. ε_0 is the absolute permittivity. $\varepsilon_r = nr^2\varepsilon_0$ is the relative permittivity [27]. Now the total optical absorption coefficient is

$$\alpha(\omega,I) = \alpha^{(1)}(\omega) + \alpha^{(3)}(\omega,I)$$

(5)

In this study we just investigate the m=0 →m=1 transition.

3 Results and discussion

Here, we use the electron density as $n^{2D} = \sigma_s =$ 3.0×1016 cm^{-3} [26], m* = 0.15m$_0$ (m$_0$ is the mass of the free electron), the potential height as V_{conf} = 1.28 eV, the outer quantum ring radius as R_{out} = 1000 A° and $n_{r=}$ = 3.2. After solving Eq. (1), calculation of the total absorption coefficient using Eq. (5) is trivial. By changing the number of wells from one to five at zero magnetic field, and assuming the inner quantum ring to be 200 A°, we compute the total absorption coefficient for the CTER-MWQRs. The results have been shown in panels (A) to (E) of Fig. 2-1.

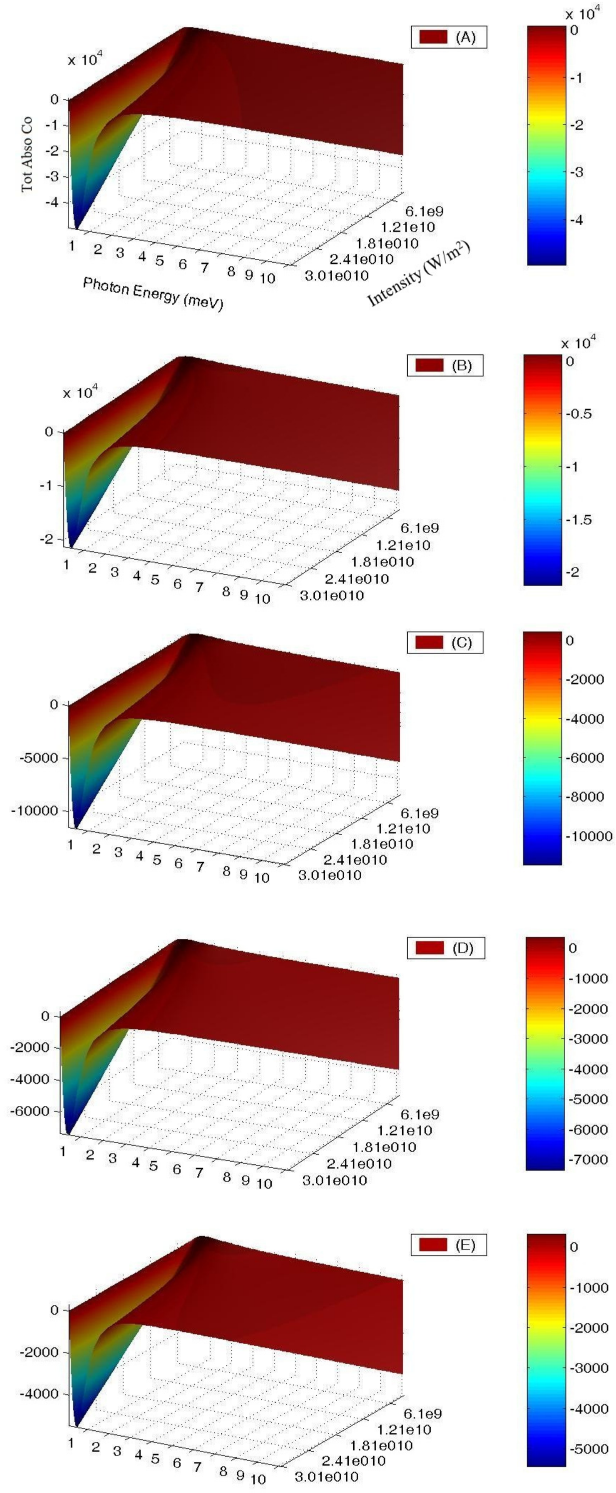


Figure 2-1. The total optical absorption coefficient versus the incident wave photon energy (meV) and optical wave intensity (W/m^2). The effects of different well number at zero magnetic field are presented. In the panels (A) to (E), 1 to 5 well numbers are investigated. The inner quantum ring radius is R_{in}=200A°.

There is a common fact in all panels of Fig. 2-1. The total absorption coefficient decreases when the intensity increases. This statement remains true even by changing the magnetic field together with the inner quantum ring radius R_{in}, see the panels of Figs. 2-2 and 2-3 together with Figs. 3-2 and 4-3. For every R_{in} and number of wells there also is similar decreasing behavior of the total absorption coefficient as intensity increases. Comparing the panels of Fig. 2-1 reveals that an increase in the well number leads to the monotonic decreasing of the total absorption coefficient; compare the color bars of these panels. By increasing the magnetic fields to 5T and 12T while retaining the R_{in} constant and equal to 200A° (Figs. 2-2 and 1-3, respectively), we see that this fact is still true. But by increasing the R_{in} to 400A° and taking the magnetic field (Fig. 3-1) equal to zero, this monotonic behavior changes. Here, the total absorption coefficient at first decreases and then increases. The turning point is the panel (C) with three numbers of wells, i.e. up to 3-wells the CTER-MWQRs total absorption coefficient decreases and then increases. By increasing the magnetic field to 5T, again the monotonic behavior of the total absorption coefficient versus the number of wells appears where by further increasing the magnetic field to 12T, we see that this monotonic behavior still persists. By increasing the R_{in} to 600A°, in all magnetic fields 0T, 5T, and 12T (Figs. 4-1, 4-2 and 4-3, respectively) again the monotonic behavior is visible. Thus, only the system with R_{in}=400A° at zero magnetic field is an exception.

In order to understand the effect of the inner quantum ring radius R_{in} at zero magnetic field, we have to compare the Figs. 2-1, 3-1, and 4-1. For example, by comparing panels (A) of the stated figures (single-well CTER-MWQRs) we see that, by increasing the R_{in}, the total absorption coefficient decrease monotonically. If we want to see this effect for systems with greater number of wells, we have to compare the other panels of these figures. If we compare the panels (B) of the afore-cited figures with each other, i.e. (double-well CTER-MWQRs), we see that the monotonic decreasing behavior of the total absorption coefficient versus R_{in} exists for systems with greater number of wells, this could also be observed by comparing the other panels. But, is this behavior true for higher magnetic fields? to answer this question we have to compare e.g. panels (A) of Figs. 2-2, 3-2, and 3-1 for

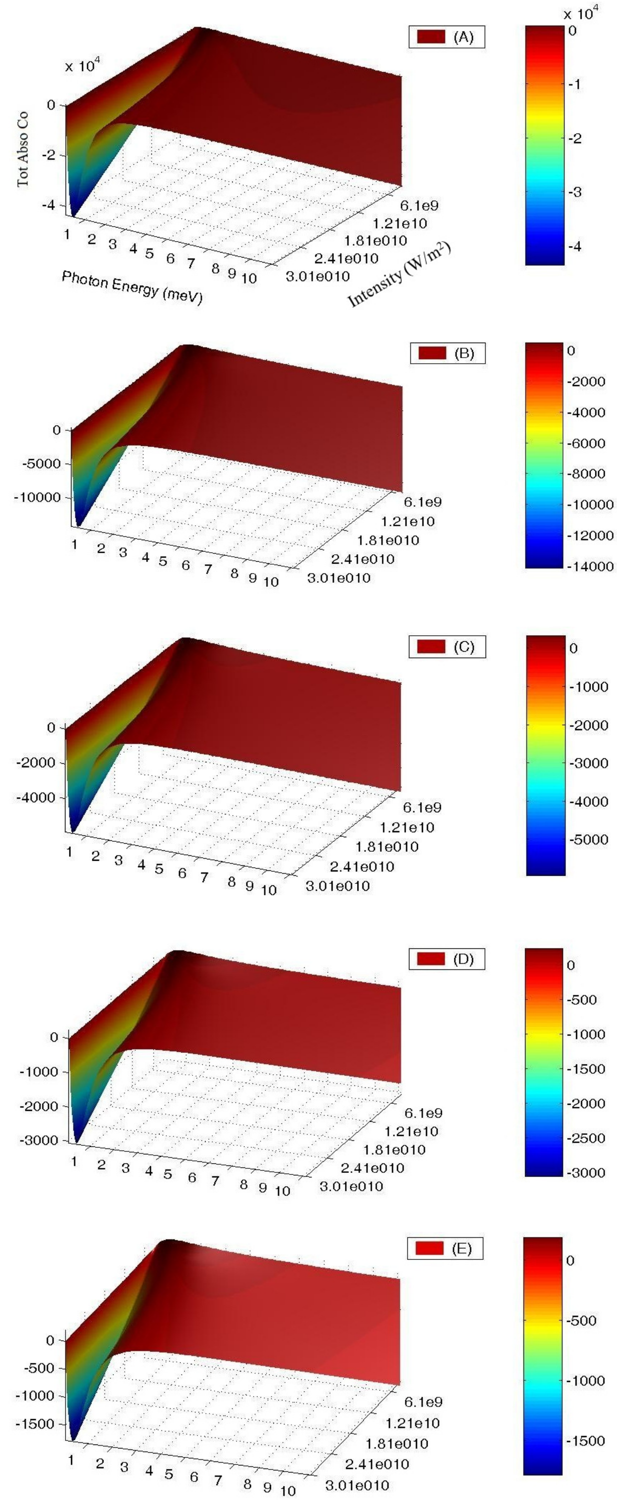


Figure 2-2. The total optical absorption coefficient versus the incident wave photon energy (meV) and optical wave intensity (W/m^2). The effects of different well number when the magnetic field is 5 T are presented. In panels (A) to (E), 1 to 5 well numbers are investigated. The inner quantum ring radius is R_{in}=200A°.

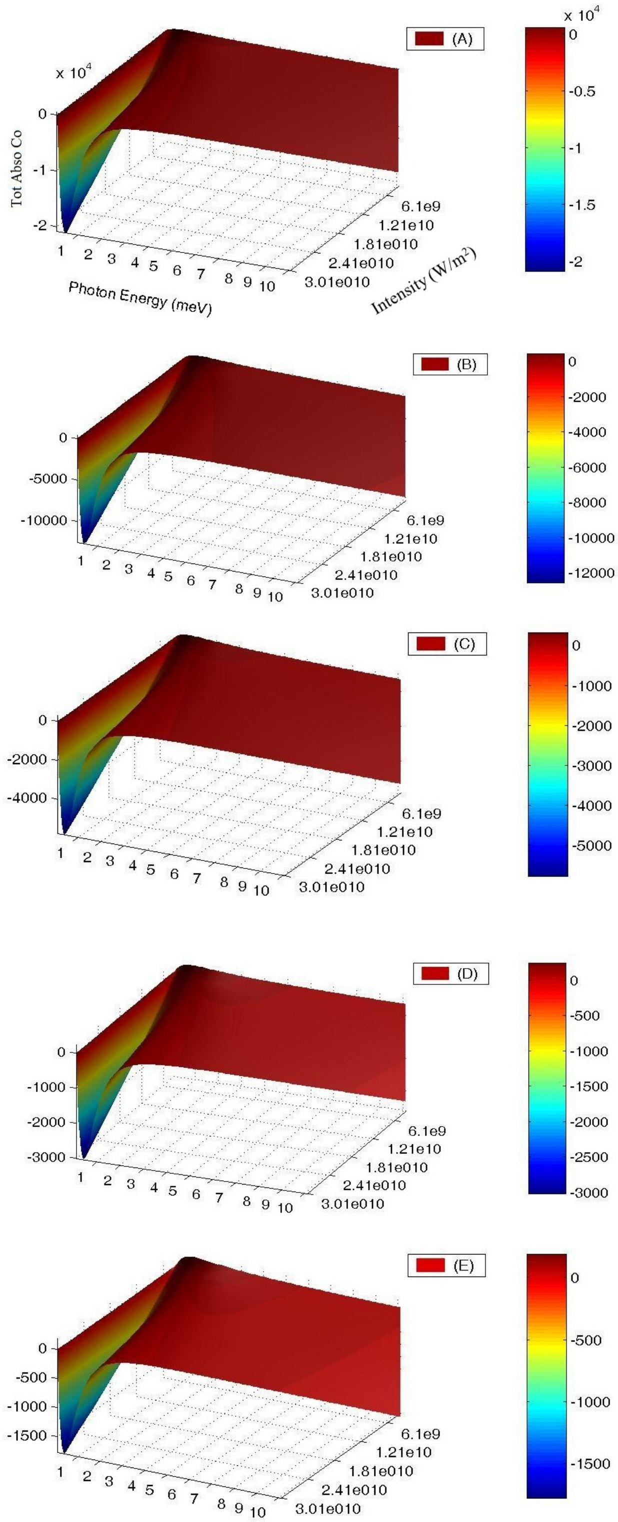


Figure 2-3. The total optical absorption coefficient versus the incident wave photon energy (meV) and optical wave intensity (W/m^2). The effects of different well number when the magnetic field is 12 T are presented. In panels (A) to (E), 1 to 5 well numbers are investigated. The inner quantum ring radius is R_{in}=200A°.

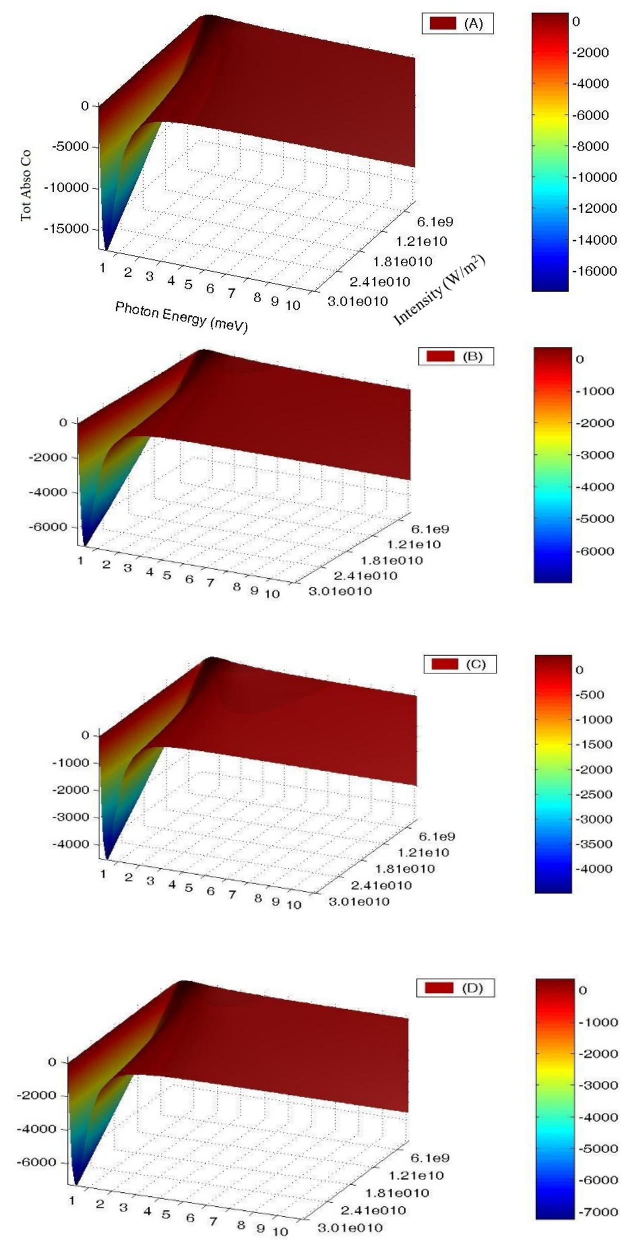


Figure 3-1. As for Fig. 2-1 regarding panels (A) to (D), the well numbers are 1 to 4, respectively. The inner quantum ring radius is R_{in}=400A°.

a magnetic field equal to 5T. Again, we see that for a 5T magnetic field, the total absorption coefficient monotonically decreases when the number of wells increases. Till now, we have seen the effects of the number of wells and inner quantum ring radius R_{in} on the total absorption coefficient at different magnetic fields. We now want to see the effect of the magnetic field on the absorption coefficient of the system. By increasing the magnetic field at fixed R_{in}=200, (Fig. 2-1, Fig. 2-2, and Fig. 2-3 respectively for magnetic fields equal to 0, 5, and 12 T), the total absorption coefficient decreases monotonically. This fact is true for systems with more number of wells (panels (B) of the figures) and higher R_{in} values, e.g. compare panels (A) or (B) of Fig. 4-1 and Fig. 4-2 respectively for zero and 5 T with Fig. 4-3 for 12 T. Finally, by comparing the slope of the decreasing total absorption coefficient versus the number of wells, we see at lower magnetic fields, the total absorption coefficient decreases more rapidly than for higher magnetic fields. This fact becomes more evident if we compare the color bars of panels (A) and (E) in Fig. 2-1 with the corresponding color bars of panels (A) and (E) in Fig. 2-3.

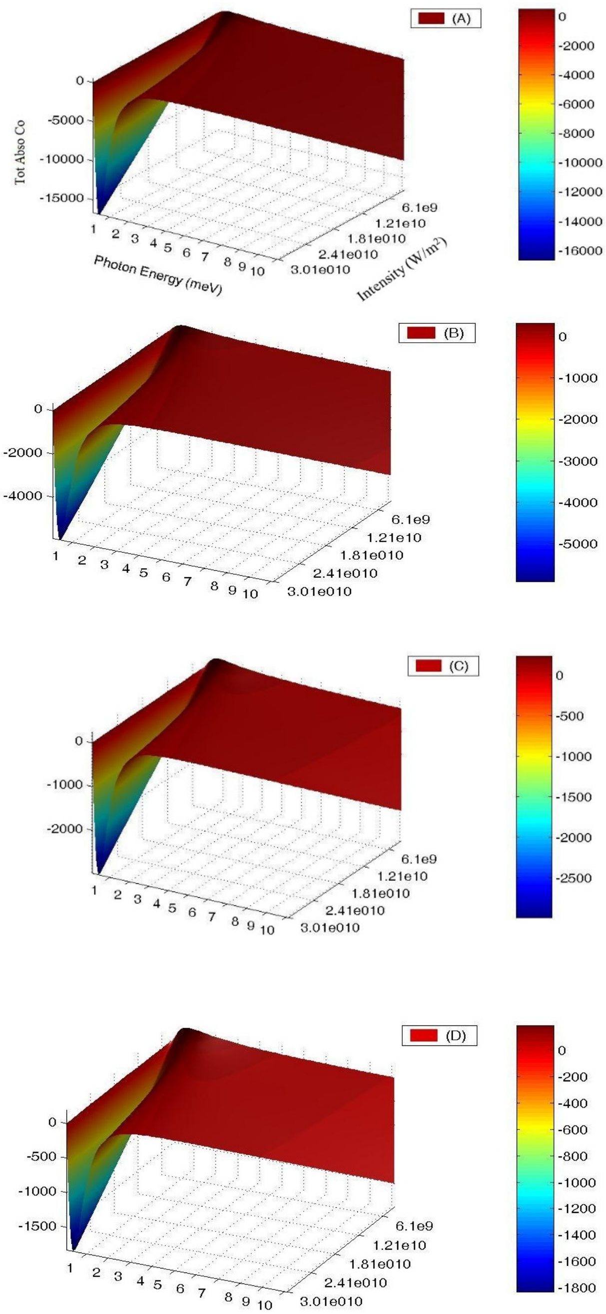


Figure 3-2. As for Fig. 2-2 regarding panels (A) to (D), the well numbers are 1 to 4, respectively. The inner quantum ring radius is R_{in}=400A°.

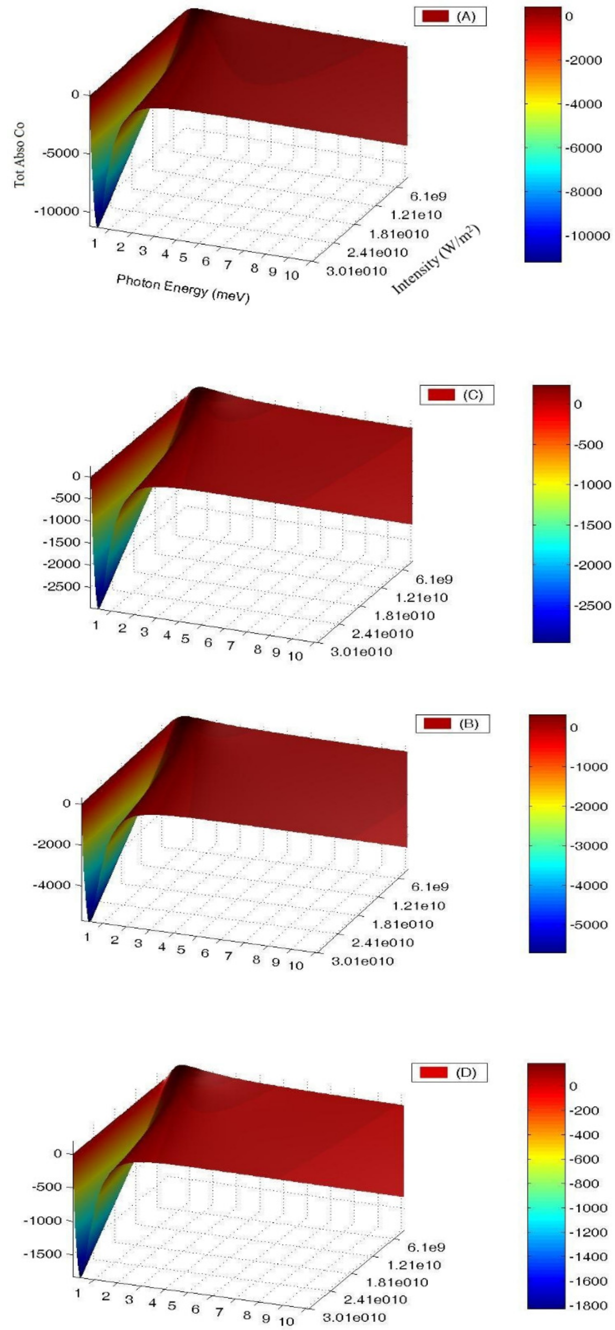


Figure 3-3. As for Fig. 2-3 regarding panels (A) to (D), the well numbers are 1 to 4, respectively. The inner quantum ring radius is R_{in}=400A°.

For more illustration purposes, we have also provided the subband energy difference, dipole matrix elements, ground state normalized wave function, and ground state energy as a function of the magnetic field in figures 4, 5 6, and 7, respectively.

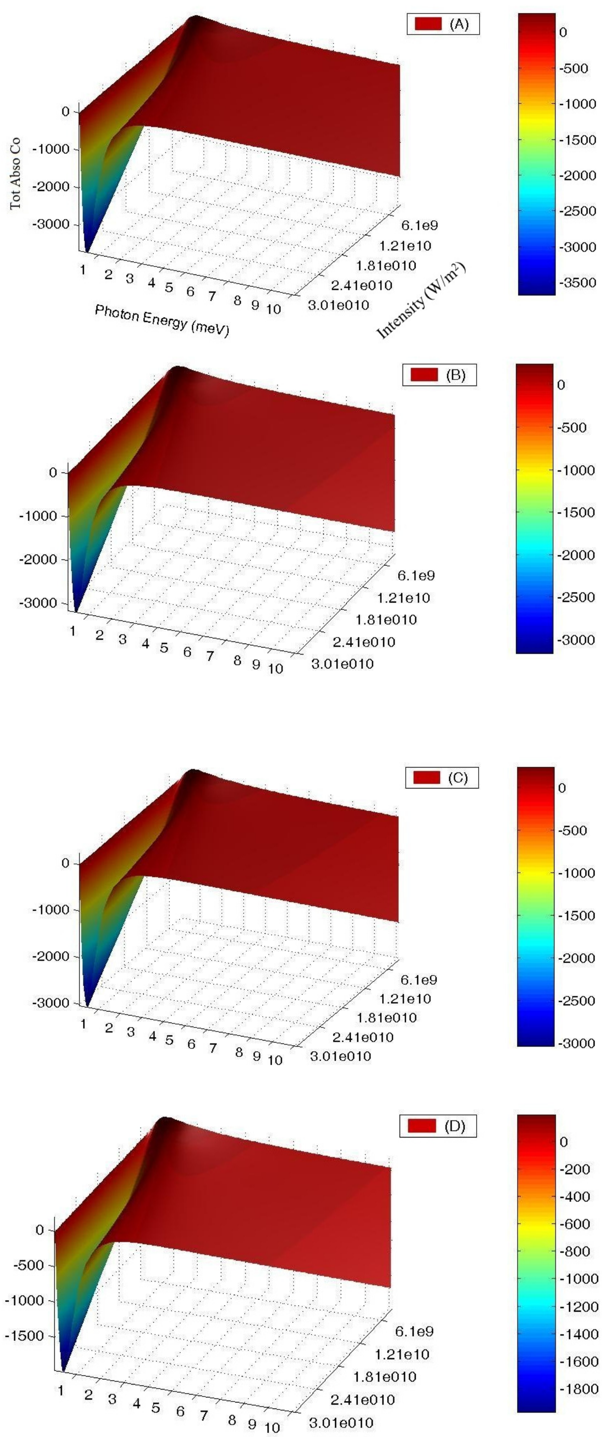


Figure 4-1. As for Fig. 2-1 regarding panels (A) to (D), the well numbers are 1 to 4, respectively. The inner quantum ring radius is R_{in}=600A°.

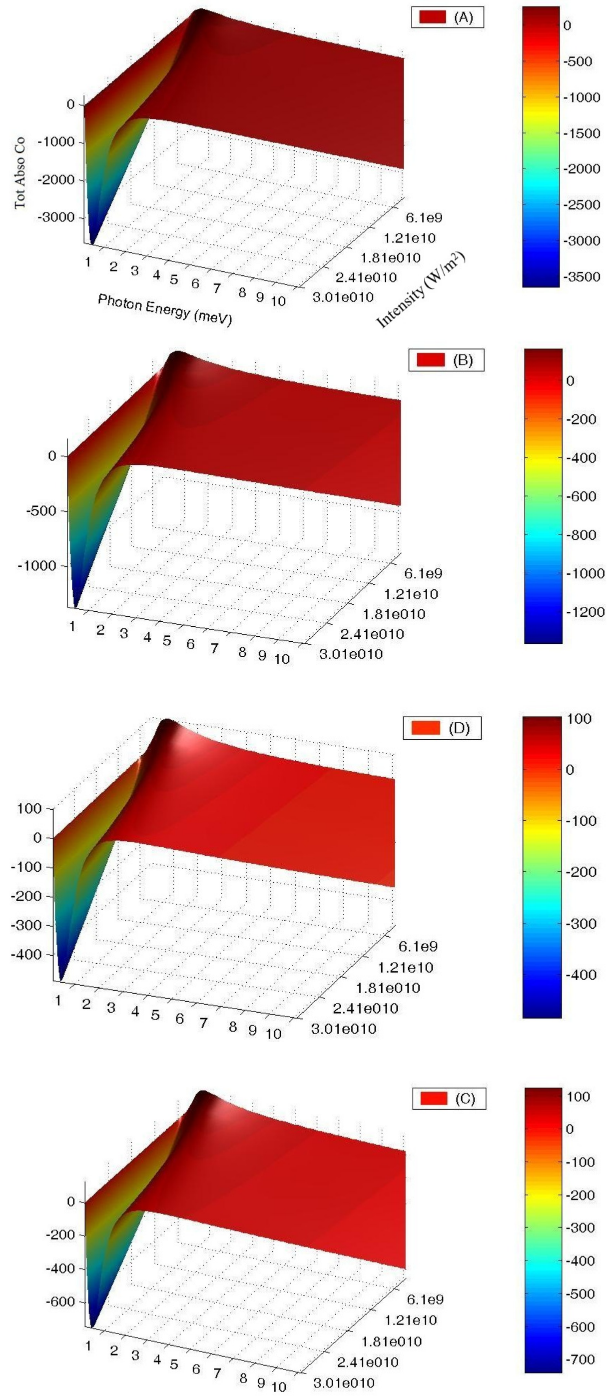


Figure 4-2. As for Fig. 2-2 regarding panels (A) to (D), the well numbers are 1 to 4, respectively. The inner quantum ring radius is R_{in}=600A°.

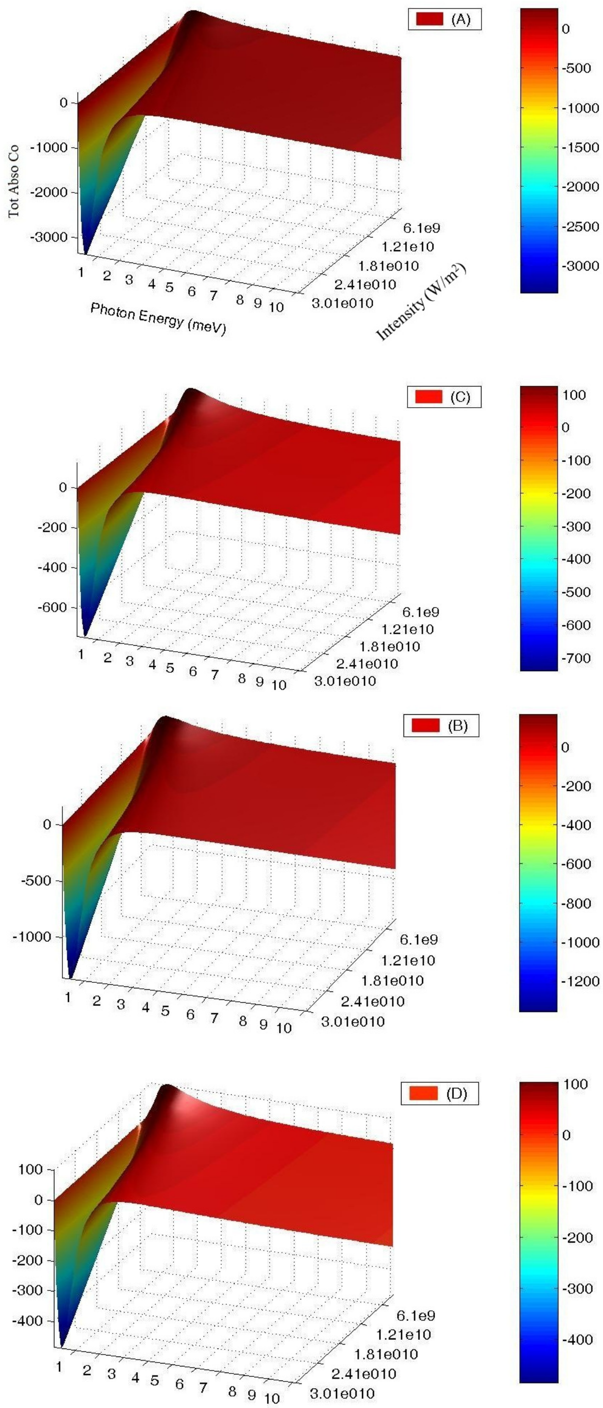


Figure 4-3. As for Fig. 2-3 regarding panels (A) to (D), the well numbers are 1 to 4, respectively. The inner quantum ring radius is R_{in}=600A°.

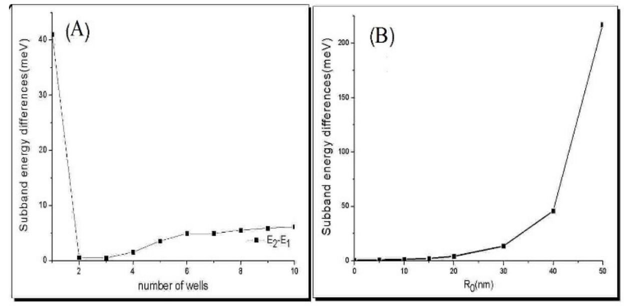


Figure 5. Panel (B): subband energy difference E_2-E_1 versus well number. Panel (C): transition energy E_2-E_1 versus inner quantum ring radius R_0 for a system with three well numbers.

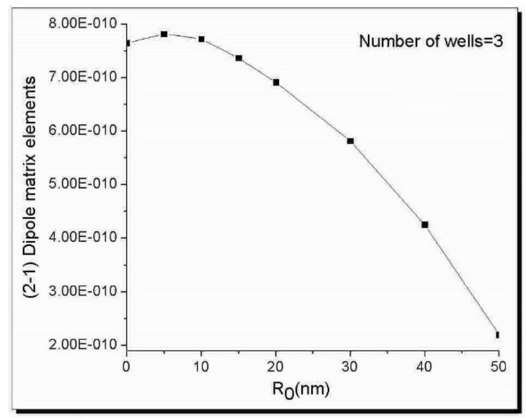
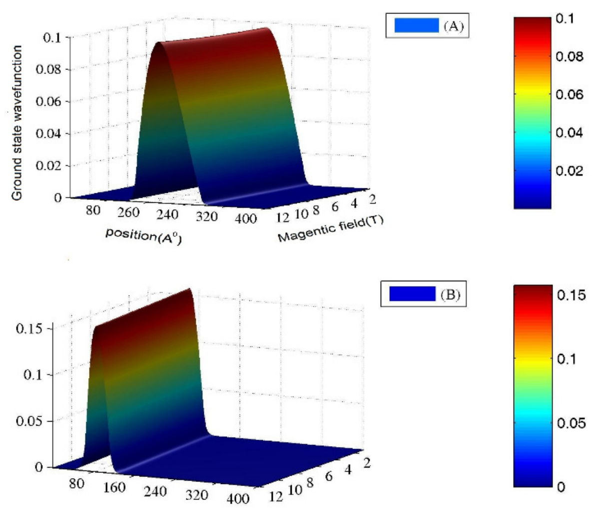


Figure 6. The dipole matrix element for a system with three numbers of wells versus ring radius R_0.



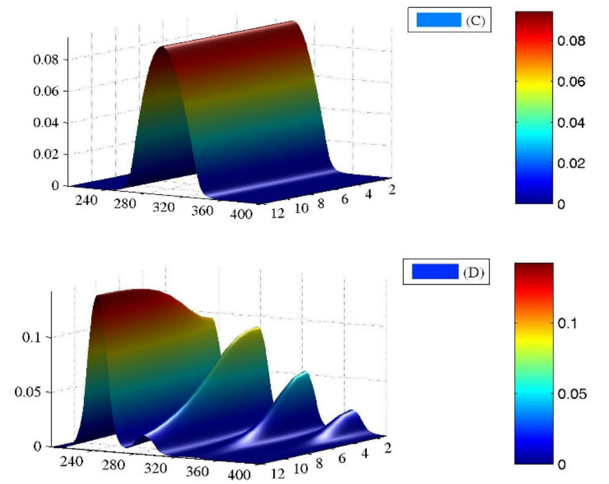


Figure 7, Ground state normalized wave function with Rout=400 A° as a function of the magnetic field (T) and position (A°). Number of wells and R_{in} in panels (A) to (D) are (0 A° & 1), (0 A° & 4), (200 A° & 1) and (200 A° & 4), respectively.

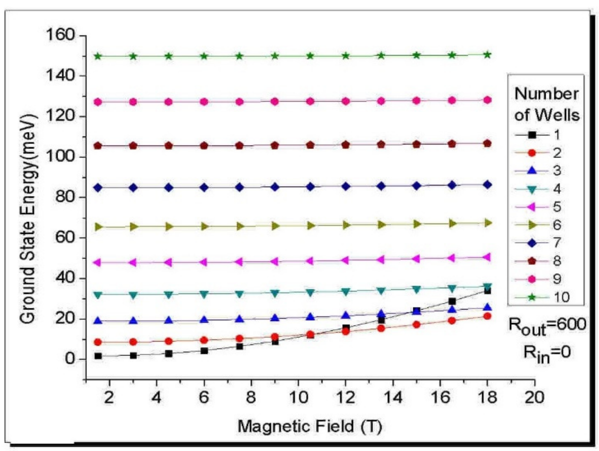


Figure 8: Ground state energy versus magnetic field for a system with different numbers of wells (1 to 10). We have assumed Rout=600 A° and Rin=0 A°.

3 Conclusions

Here, we consider the effects of the intensity and external magnetic field on the optical absorption coefficient of the multi-well AlN/GaN quantum rings. Besides, the effects of the well number and inner quantum ring radius R_{in} are also explored. We showed that, for each inner quantum ring radius R_{in}, magnetic field and number of wells, the total absorption coefficient decreased when the intensity increased. By increasing the number of wells, the total absorption coefficient monotonically decreased. The total absorption coefficient at first decreased (up to 3-wells CTER-MWQRs) and then increased when the number of wells increased. By increasing the R_{in}, the total absorption coefficient monotonically decreased. This monotonic decreasing characteristics of the total absorption coefficient as a function of R_{in} existed for systems with more number of wells and higher magnetic fields. By increasing the magnetic field at fixed R_{in}, the total absorption coefficient monotonically decreased which was true for systems with larger well number and higher R_{in} values. Finally, the total absorption coefficient decreased more rapidly at lower magnetic fields compared to higher ones.

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