Impurity-related optical-absorption spectra in GaAs-$Ga_{1-x}Al_xAs$ superlattices with an in-plane magnetic field

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(Received 26 September 1997; revised manuscript received 6 January 1998)

The effects of applied magnetic fields on the binding energy and the optical-absorption spectra associated with transitions from the first Landau valence level to a shallow donor-impurity band in GaAs-$Ga_{1-x}Al_xAs$ superlattices are studied for magnetic fields applied parallel to the interfaces of the heterostructure. The donor-related magneto-absorption spectra are calculated within the effective-mass approximation using a variational procedure. Electron and hole magnetic envelope wave functions were obtained by an expansion in terms of sine functions. We consider a homogeneous donor distribution in the superlattices and analyze the theoretical impurity-related magnetoabsorption spectra for superlattices with different well widths, barrier lengths, and for various applied magnetic fields. We observed that the impurity binding energy decreases as the impurity approaches the barrier for all magnetic fields. For impurities located at the center of the wells the binding energy always increases with the applied magnetic field. The main feature found in the theoretical spectra was an absorption edge associated with transitions involving impurities at the center of the wells. The energy for the peak position shows a linear dependence for magnetic fields higher that 4 T. For lower fields the dependence is nonlinear. Also, we found that the intensity of the peak increases with the applied magnetic field. [S0163-1829(98)07527-4]

I. INTRODUCTION

There has been an increasing interest, both experimental and theoretical, in the investigation of quasi-two-dimensional (Q2D) systems, such as semiconductor heterostructures, quantum wells, and superlattices (SL's), because of their intrinsic physical interest and their technological applications in electronic devices. The understanding of the nature of impurity states in semiconducting heterostructures is a subject of considerable technical and scientific relevance. Transition energies between donor states in low-dimensional systems have been experimentally observed by far-infrared and intersubband spectroscopy, and various theoretical investigations have been performed in order to understand the nature and properties of these impurities. Since the optical and transport properties of semiconductor materials are strongly influenced by both these doping impurities and the structures of the Q2D systems, the knowledge of the effect of the confining potential barriers on the donor states is important. Bastard[1] reported the first calculation for binding energies of hydrogenic impurities in quantum wells (QW's) with an infinite potential in the barriers. Several groups[2,3] have extended the work of Bastard to calculate the low-lying energy levels of the donor in the finite high barrier QW. Chaudhuri and Bajaj[4] included the effect of the band nonparabolicity in their calculation, where the effective mass of the electron was only associated with the lowest subband of the QW. Chaudhuri[5] extended the variational calculation of the ground-state energy of a donor electron in a QW to the situation of a multiple-well structure. This calculation was generalized to a superlattice by Lane and Greene,[6] who also calculated the energy of low-lying excited states $(2p_{\pm})$ of a hydrogenic donor at an arbitrary position. Helm *et al.*[7] extended these calculations to higher excited states (i.e., $1s, 2s, 2p_{\pm}, 2p_z$), where they included the spatial dependence of the electron mass.

Shi *et al.*[8] presented a theoretical investigation of the properties of shallow donor impurities in a $GaAs/Al_xGa_{1-x}As$ superlattice in the presence of a magnetic field applied along the growth axis. They obtained the energy levels of several lowest donor excited states as functions of the magnetic-field strength, well width, and the donor position. The magnetopolaron effect on these donor energies was studied within second-order perturbation theory in which a formal summation over all electron states is performed. The effect of band nonparabolicity is also included to correctly explain magneto-optic experimental results at high magnetic fields.

The optical absorption spectra associated with transitions involving shallow impurities in QW's and QWW's was studied by Bastard,[1] Oliveira *et al.*,[9] and Deng.[10] The effects of applied magnetic fields on the optical-absorption spectra associated with transitions from the Landau valence magnetic levels to shallow donor states in GaAs-(Ga,Al)As quantum wells, for magnetic fields applied perpendicular to the heterostructure interfaces were studied by Barbosa *et al.*[11]

For a magnetic field in the growth direction, the cyclotron motion of electrons is in the plane of the superlattice parallel to the interface. The quantizations caused by the magnetic field and the confinement of electrons in the growth direction are independent, and the electronic magnetic energy levels in superlattices are relatively simple. In the case the magnetic field is applied parallel to the interfaces, the electronic cyclotron motion is in the growth direction, and the quantum energy levels are determined by the magnitudes of the magnetic field and the width of the quantum wells.

Belle *et al.*[12,13] have shown, both theoretically and experimentally, that transitions between well-defined Landau levels

may be seen in the interband magnetoluminescence only for transitions that are related to Landau levels with energies within the first electron and hole minibands. De Dios-Leyva *et al.*[14–16] calculated the absorption coefficient of GaAs-(Ga, Al) As SL's under the action of an in-plane magnetic field for both interband and intraband transitions between electronic and hole magnetic levels. The observation of an intersubband donor-absorption line induced by applying an in-plane magnetic field in a QW was reported by Brozak.[17]

Skromme *et al.*[18] studied the cyclotron motion of electrons in couple-well GaAs-(Ga,Al)As superlattices by photoluminescence of conduction band to acceptor transitions in magnetic fields up to 13 T, applied either parallel or perpendicular to the layers. For parallel fields, three different regimes are observed as the ratio of the cyclotron radius to the superlattice period is reduced, namely, tunneling cyclotron motion within the miniband, miniband breakdown, and finally a transition from electric to magnetic quantization. Notice that Skromme *et al.*[18] were essentially concerned with *acceptor-related photoluminescence* spectra, which was theoretically explained by Latgé *et al.*,[19,20] whereas in this work we are concerned with the *donor-related magneto-optical absorption* spectra, which could in principle be easily studied for donor-doped SL's samples such as the ones investigated by Skromme *et al.*[18]

In this work we present a systematic study of the magneto-optical absorption spectra associated with transitions from the first valence Landau level to donor impurity states in GaAs-(Ga,Al)As superlattices under the action of magnetic fields applied perpendicular to the growth direction of the heterostructure. The temperature is assumed high enough to have ionized donor states and to make possible the impurity-related absorption phenomena. Section II is devoted to the presentation of some theoretical aspects and to the calculation of the transition probability per unit of time associated with the donor-related magneto-optical absorption spectra. Results and a discussion are presented in Sec. III and our conclusions are in Sec. IV.

II. THEORY

We consider an in-plane magnetic field applied along the y direction, with the z axis along the growth direction of the GaAs-(Ga,Al)As superlattice (with the origin at the center of the central well); i.e., the magnetic field is given by $\mathbf{B}=B\hat{j}$, and with a gauge choice for the vector potential such that $\mathbf{A}=zB\hat{i}$. The Hamiltonian for the carrier in the conduction (or valence) band, within the effective mass approximation and using a parabolic-band model, is

$$\mathbf{H}^0=\frac{1}{2m^*}\left[\mathbf{P}+\frac{e}{c}\mathbf{A}\right]^2+V(z), \tag{1}$$

where $-e$ is the electron charge, m^* is the carrier effective mass, and $V(z)$ is the superlattice potential, equal to zero in the wells and to V_b in the barriers, V_b being about 60% (40%) of the band-gap difference ΔE_g between $Ga_{1-x}Al_xAs$ and GaAs, with $\Delta E_g(\mathrm{eV})=1.247x$, for the conduction (valence) band.[9]

If one uses the translational symmetry in the x and y directions, the eigenfunctions and eigenvalues of Eq. (1) may be chosen as

$$\Psi^0(\mathbf{r})=\varphi_{n,k_x}(z)e^{ik_xx+ik_yy} \tag{2}$$

and

$$E^0(k_x,k_y)=E_n(k_x)+\frac{\hbar^2k_y^2}{2m^*}, \tag{3}$$

where $n=0,1,2,\ldots$, are the Landau-subband indices, and k_x, k_y are the wave-vector components in the x-y plane. In Eqs. (2) and (3), $\varphi_{nk_x}(z)$ and $E_n(k_x)$ are the eigenfunctions and eigenvalues of the Hamiltonian obtained from Eq. (1), with the substitutions of p_x by $\hbar k_x$ and p_y by zero, which describe states with well-defined values of the cyclotron orbit center $z_0=k_xl_B^2$, with $l_B=(\hbar c/eB)^{1/2}$ being the cyclotron radius. The magnetic levels and envelope wave functions were obtained by expanding $\varphi_{nk_x}(x)$ in terms of sine functions, and diagonalizing the corresponding Hamiltonian, as reported by Xia and Fan,[19] i.e.,

$$\varphi_{nk_x}(z)=\left[\frac{2}{L}\right]^{1/2}\sum_{m=1}C_m\sin\left[\frac{m\pi z}{L}+\frac{m\pi}{2}\right], \tag{4}$$

and therefore, the C_m are straightforwardly obtained for a given magnetic field and superlattice potential.[19]

In the presence of a shallow donor impurity, the Hamiltonian of one electron is

$$\mathbf{H}^1=\mathbf{H}^0-\frac{e^2}{\varepsilon_0 r}, \tag{5}$$

where $\varepsilon_0=12.35$ is the dielectric constant of GaAs and $r=[x^2+y^2+(z-z_i)^2]^{1/2}$ is the electron's position relative to the impurity where z_i is the position of the impurity along the growth direction.

The trial wave function considered is

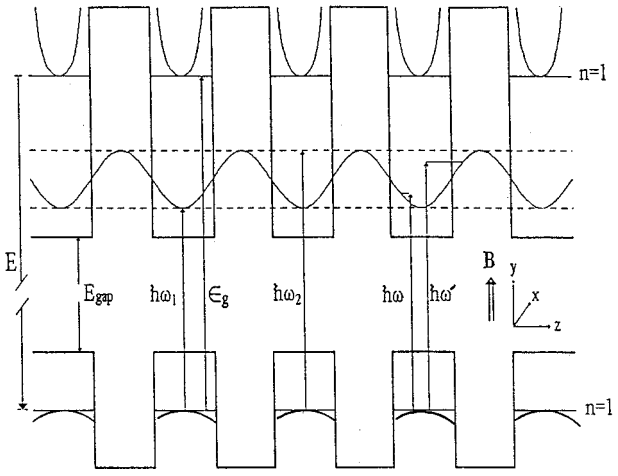

FIG. 1. Schematic representation of some possible absorption transitions from the valence magnetic levels to donor impurity ground-state in a GaAs-(Ga,Al)As superlattice. The dependence of the binding energy as a function of the donor impurity position along of the heterostructures is presented.

TABLE I.

Superlattice	well width (Å)	barrier width (Å)	$A1$ concentration	conduction effective mass	valence effective mass
1	64	26	0.21	0.0816	0.64
2	540	10	0.25	0.0655	0.3
3	135	18	0.27	0.0655	0.3

$$\Psi^I(\mathbf{r})=\left[\frac{2}{L}\right]^{1/2} N\sum_{m=1} C_m \sin\left[\frac{m\pi z}{L}+\frac{m\pi}{2}\right] e^{-\lambda r}, \quad (6)$$

with λ being a variational parameter obtained by minimizing[9,11,20] the impurity energy, and N the normalization factor. The binding energy of the impurity is given by

$$E_b(\mathbf{z}_i)=E_1-\langle \mathbf{H}^I\rangle, \quad (7)$$

where $\langle \mathbf{H}^I\rangle$ is the total energy with impurity and E_1 is the energy of the first magnetic level which is independent of k_x.

For transitions from the first valence level to a donor impurity level, we have for the initial and final states

$$\psi_1^i(\mathbf{r})=\left[\frac{2}{L}\right]^{1/2}\sum_{m=1} C_m \sin\left[\frac{m\pi z}{L}+\frac{m\pi}{2}\right] e^{ik_x x+ik_y y} u_i(\mathbf{r}), \quad (8)$$

$$w_1^f(\mathbf{r})=\left[\frac{2}{L}\right]^{1/2} N\sum_{m=1} C_m \sin\left[\frac{m\pi z}{L}+\frac{m\pi}{2}\right] e^{-\lambda r} u_f(\mathbf{r}), \quad (9)$$

where $u_i(\mathbf{r})$ and $u_f(\mathbf{r})$ are the periodic parts of the Bloch states for the initial and final states.

Taking the energy origin at the first conduction subband as depicted in Fig. 1, we have for the energy of the initial (first valence level) state

$$E_i=-\epsilon_g, \quad (10)$$

where ϵ_g is given by

$$\epsilon_g=E_{\text{gap}}+E_{1c}+E_{1v}, \quad (11)$$

with $E_{\text{gap}}=1.424$ eV (Refs. 19 and 21) being the bulk GaAs band gap and E_{1c} (E_{1v}) is the energy of the first Landau level in the conduction (valence) band.

The energy of the final state is

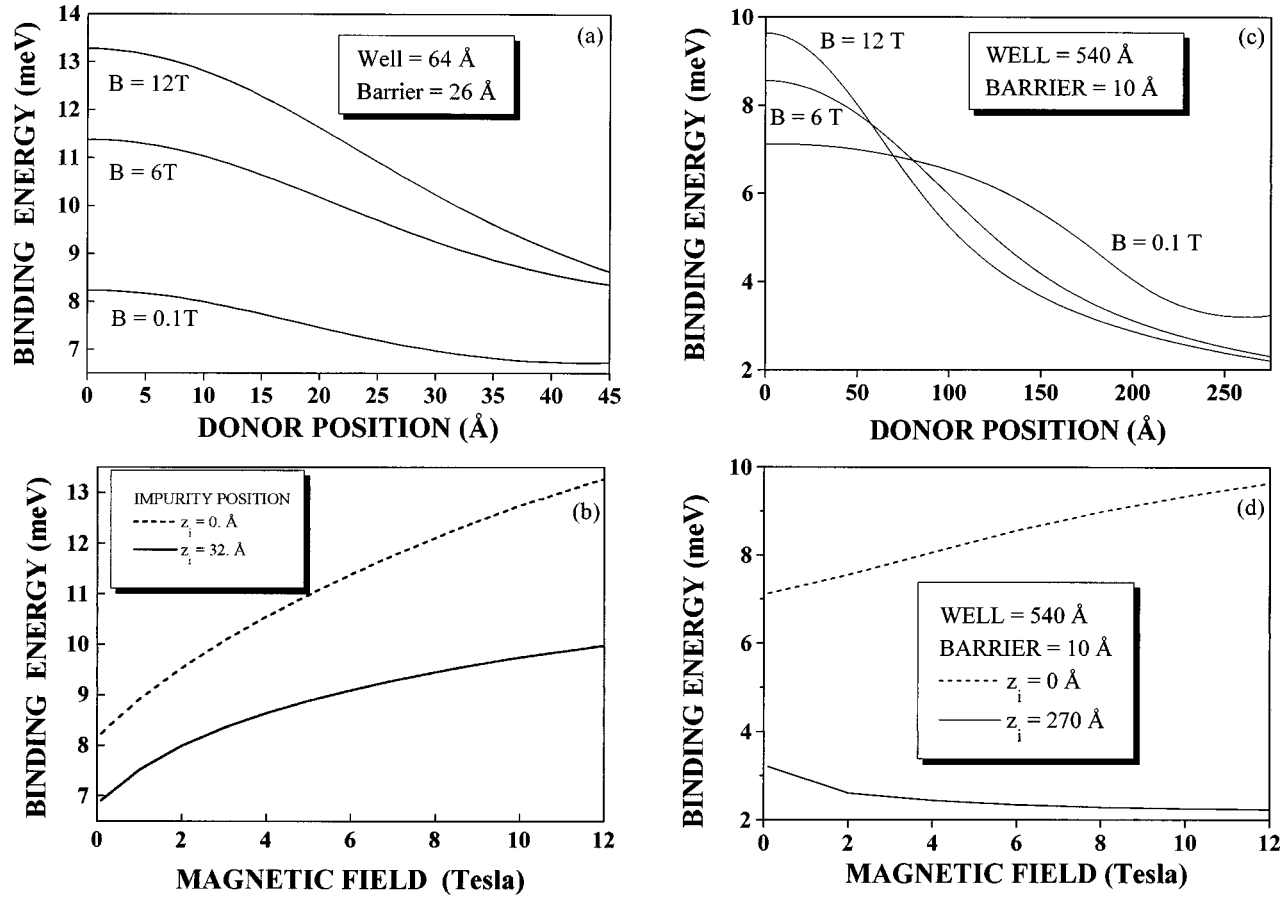

FIG. 2. Donor binding energy as a function of the impurity position and magnetic field for GaAs-(Ga,Al)As superlattices. In Figs. 2(a) and 2(b), well width=64 Å and barrier width=26 Å. In Figs. 2(c) and 2(d), well width=540 Å and barrier width=10 Å.

$$E_f = -E_b(\mathbf{z}_i). \tag{12}$$

The transition probability per unit time for valence-to-donor transitions associated with a donor impurity located at $\mathbf{z}_i$ is proportional to the square of the matrix element of the electron-photon interaction $H_{\rm int}$ between the wave functions of the initial state (first Landau valence level) and final (impurity) states, i.e.,

$$W(\omega) = \frac{2\pi}{\hbar} \sum |\langle f|H_{\rm int}|i\rangle|^2 \delta(E_f - E_i - \hbar\omega) \tag{13}$$

with

$$H_{\rm int} = \frac{e}{m_0 c} \mathbf{A}_{\rm ph} \cdot \left(\mathbf{P} + \frac{e}{c} \mathbf{A} \right), \tag{14}$$

where $\mathbf{A}_{\rm ph}$ is the radiation-field vector potential. Following the effective mass approximation, the above matrix element may be written as[11,22]

$$\langle f|H_{\rm int}|i\rangle \cong \frac{e}{m_0 c} \mathbf{A}_{\rm ph} \cdot \mathbf{P}_{fi} S_{fi} \tag{15}$$

with

$$\mathbf{P}_{fi} = \frac{1}{\Omega} \int_\Omega d\mathbf{r} u_f^*(\mathbf{r}) \mathbf{p} u_i(\mathbf{r}) \tag{16}$$

and

$$S_{fi} = \int d\mathbf{r} F_f^*(\mathbf{r}) F_i(\mathbf{r}), \tag{17}$$

where Ω is the volume of the unit cell and F_f (F_i) is the envelope function for the final (initial) state. For the case of the donor impurity we have for $S_{fi} = S_{fi}(\mathbf{z}_i, k_x, k_y)$,

$$S_{fi} = \frac{2N}{L} \sum_{m,m'} C_m C_{m'} \int d^3r \sin\left[\frac{m\pi z}{L} + \frac{m\pi}{2} \right] \times \sin\left[\frac{m'\pi z}{L} + \frac{m'\pi}{2} \right] e^{ik_x x + ik_y y - \lambda r}. \tag{18}$$

For a GaAs-(Ga,Al)As superlattices with one impurity at z_i, the transition probability per unit time for valence to donor transitions is given by

$$W(\mathbf{z}_i, \omega) = W_0 \frac{\sqrt{m_v^*} L_y \hbar}{2\sqrt{2} a_0^2 l_b^2} \times \int_0^d dz_0 S_{fi}^2 \left(z_i, z_0, \sqrt{\frac{2m_v \Delta}{\hbar^2}} \right) \frac{Y(\Delta)}{\sqrt{\Delta}}, \tag{19}$$

where a_0 is the Bohr radius and $Y(\Delta)$ is the step function. In this expression we have for Δ and W_0,

$$\Delta = \hbar\omega - \epsilon_g + E_b(\mathbf{z}_i), \tag{20}$$

$$W_0 = \frac{4m_0}{\hbar^3} a_0^2 \left[\frac{e}{m_0 c} \right]^2 |\mathbf{A}_{\rm ph} \cdot \mathbf{P}_{fi}|^2. \tag{21}$$

For a homogeneous distribution of impurities and assuming that the superlattice parameters are much larger than the lattice parameter, one has for the total transition probability per unit of time

$$W(\omega) = \frac{1}{L} \int_{-L/2}^{L/2} dz_i W(z_i, \omega). \tag{22}$$

We would like to stress that we are assuming that the temperature is such that essentially all donors are ionized (i.e., $k_B T \gg$ Ry*, where Ry* is the donor effective Rydberg; no other temperature effects are explicitly taken into account). Also, we neglect effects both of the band-gap renormalization due to the conduction-band electrons introduced by the ionized donors, as well as of any process involving excitons such as bound-to-impurity excitons, etc.

III. RESULTS AND DISCUSSION

The characteristic values (well width, barrier width, period, Al concentration, effective mass for conduction and valence bands) of the studied superlattices are shown in Table I. In what follows, therefore, we performed the calculation of the magneto-optical donor-related absorption spectra for

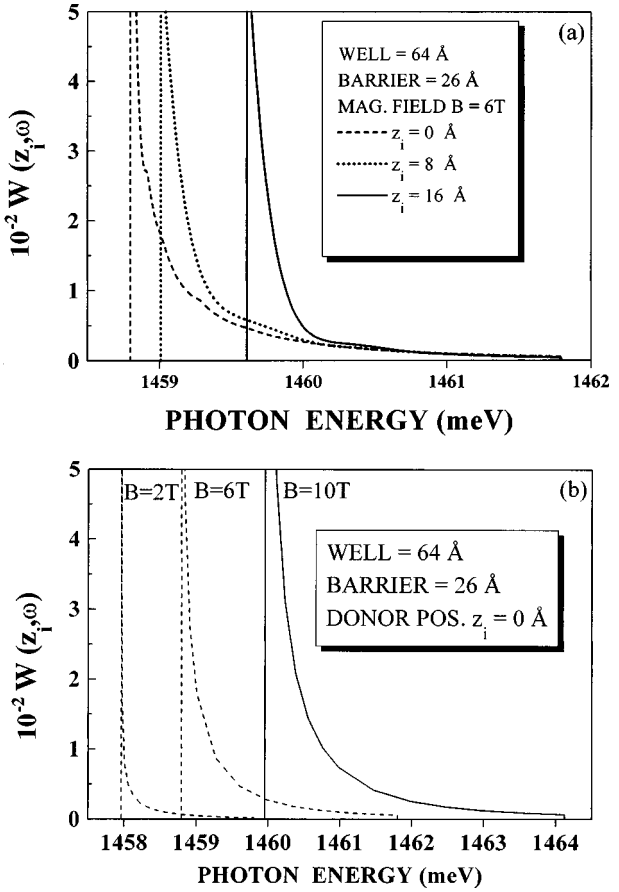

FIG. 3. Absorption probability per unit time $W(z_i, \omega)$ as a function of energy photon [in units of W_0; see Eq. (21)] for valence to donor transitions in a GaAs-(Ga,Al)As superlattice of well width = 64 Å and barrier width = 26 Å. (a) Fixed values of impurity position $z_i = 0$, 8, 16 Å and magnetic field $B = 6$ T. (b) Different magnetic fields $B = 2$, 6, 8, 10 T and a fixed impurity position at $z_i = 0$ Å.

SL's with barrier and well widths corresponding to the samples studied by Skromme *et al.*[18]

A schematic representation of a portion of a GaAs-(Ga,Al)As superlattice doped with an homogeneous distribution of the donor impurities is shown in Fig. 1. The edges for optical absorption spectra associated with transitions from the first valence subband to the donor-impurity band is represented by $\hbar\omega_1$ and to the first conduction subband by ε_g. The transition $\hbar\omega_2$ corresponds to the absorption associated with impurities located at the center of the barriers.

In Fig. 2 we display the donor binding energy as a function of the donor position and applied magnetic field. For the superlattice 1 (well=64 Å, barrier=26 Å) it is observed that the binding energy decreases as the impurity approaches to the barrier [Fig. 2(a)], due to the fact that potential barrier unfastens the electron from the impurity. The binding energy is enhanced with the applied magnetic field for any donor position [Fig. 2(b)], due to the increase of the magnetic confinement. The binding energy as a function of the donor position for the superlattice 2 [Fig. 2(c)], presents a behavior similar to that displayed in Fig. 2(a) for the superlattice 1; however, in superlattice 2, the curves present a crossover for different values of the magnetic field. We observed that the crossover occurs for impurity positions closer to the center of the wells as the magnetic field increases. In Fig. 2(d) we observed that for an impurity located at the center of the well, the binding energy increases with the magnetic field as in the case of superlattice 1, while, for example, for an impurity located next to the border of the wells, the binding energy decreases with the applied magnetic field because the electronic amplitude probability increases as the magnetic field is augmented, but simultaneously it is repelled by the potential barrier, an effect that is stronger each time the impurity is closer to the barrier, reflecting how the increasing of the magnetic field weakens the carrier tunneling through the barriers and consequently the repulsion by the barrier diminishes the binding energy. On the contrary, for impurities at the center of the wells the electron is more bound as the magnetic field increases and the effect of the potential barrier (that is, the geometric confinement), otherwise present, is negligible.

The transition probability per unit of time $W(z_i,\omega)$ is presented in Fig. 3 as a function of the photon energy $\hbar\omega$. In Fig. 3(a) we present $W(z_i,\omega)$ for one impurity localized at $z_i=0$, 8, and 16 Å, for a magnetic field equal to 6 T. For a fixed value of the impurity position there is a range of photon energies for which the transition is possible, due to the parabolic dispersion relation of the first valence band. The largest transition probability is found for $\Delta=\hbar\omega-\epsilon_g+E_b(\mathbf{z}_i)=0$, i.e., for the transition from the top of the first valence subband to the impurity position z_i. The transition probability $W(z_i,\omega)$ is shown in Fig. 3(b) for one impurity located at the center of any well of the superlattice and for different values of the applied magnetic field. We observe that the

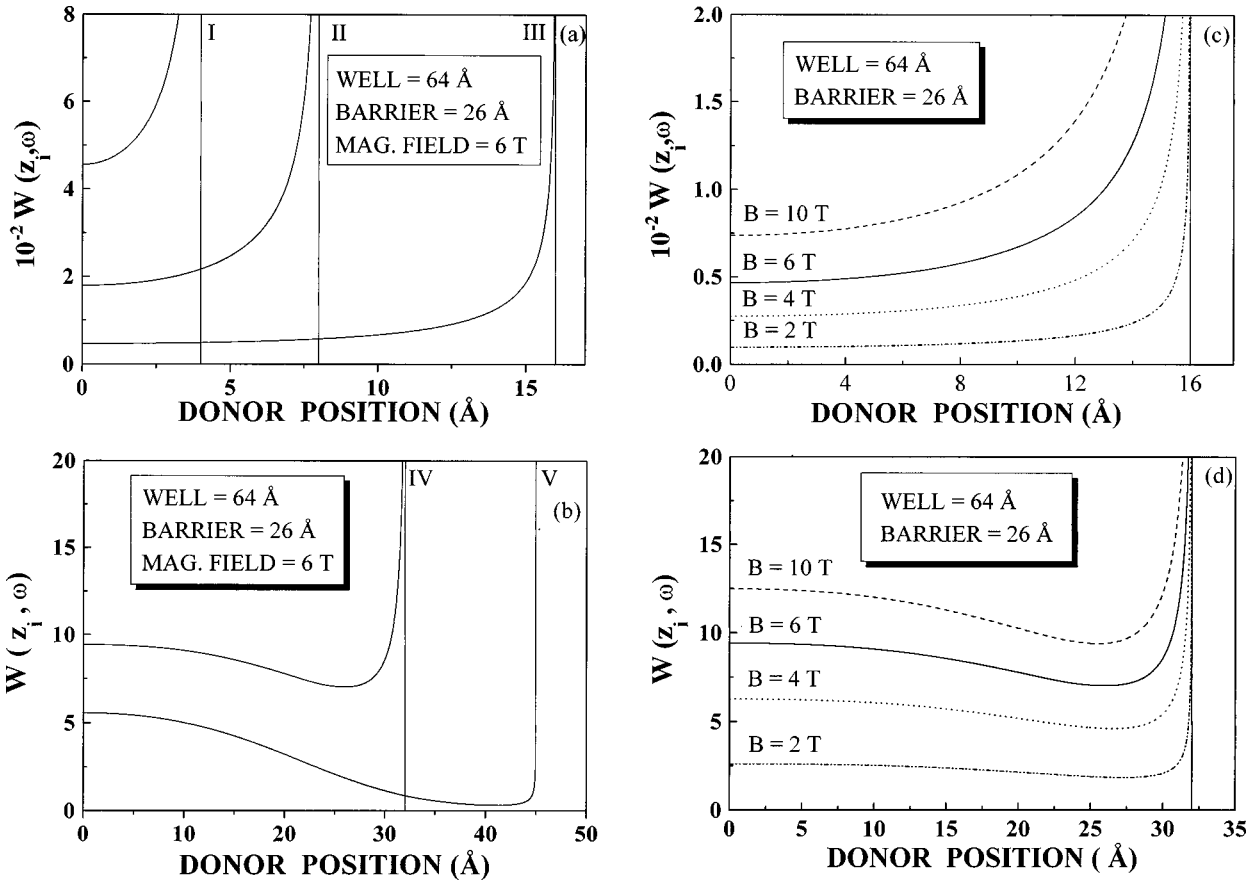

FIG. 4. Absorption probability per unit time $W(z_i,\omega)$ as a function of donor position [in units of W_0; see Eq. (21)] for valence to donor transitions in a GaAs-(Ga,Al)As superlattice of well width=64 Å and barrier width=26 Å. Curves I–V in (a) and (b) correspond to fixed values of photon energy 1458.84, 1459.00, 1459.61, 1461.07, and 1461.80 meV, respectively. (c) and (d): Different photon energies (different magnetic fields) that satisfy $\Delta=\hbar\omega-\epsilon_g+E_b(z_i=16\text{ Å})=0$ and $\Delta=\hbar\omega-\epsilon_g+E_b(z_i=32\text{ Å})=0$, respectively.

energy range of the spectra is enhanced and the position of the largest transition probability displaces to higher values in energy as the magnetic field increases. This reflects the behavior of the conduction and valence magnetic levels as well as the increment of the binding energy with the applied magnetic field.

The transition probability per unit of time $W(z_i,\omega)$ as a function of the donor position, is presented in Fig. 4. For a magnetic field $B=6$ T, we present $W(z_i,\omega)$ for some fixed values of $\hbar\omega$ [Figs. 4(a) and 4(b)]. Curves I to V correspond to values of $\hbar\omega$ equal to 1458.84, 1459.00, 1459.61, 1461.07, and 1461.80 meV, respectively. It is clear that, for a fixed value of $\hbar\omega$ only a fraction of the impurity band contributes to the absorption. We observed that for all values of the photon energy, the transition probability diverges at impurity positions for which $\Delta=\hbar\omega-\epsilon_g+E_b(\mathbf{z}_i)=0$. This is because the magnetic field applied parallel to the interfaces of the superlattices transforms the bidimensional system in an unidimensional one, i.e., the system only presents one parabolic dispersion relation. Curves I–III are similar to those obtained for the absorption transition probability in cylindrical quantum well wires,[23] i.e., $W(z_i,\omega)$ is always an increasing function with the donor position up to the limit impurity position for which it diverges. In curves IV and V it is shown how $W(z_i,\omega)$ decreases for some impurity positions and afterwards it increases up to diverge. The behavior of the transition probability $W(z_i,\omega)$ is related directly with the overlapping between the wave functions of the initial and final states which is a growing function with the donor position for photon energies corresponding to curves I–III (associated with impurities distant from the barriers), while for curves IV and V (associated with impurities close to the barriers) the overlapping is a decreasing function of the impurity position, due to both magnetic and geometrical confinement. It is observed that for impurities located at the center of the wells, the transition probability $W(z_i=0,\omega)$ diminishes as the photon energy increases. This is due to the increment in the overlapping between the wave functions of the initial and final states related with transitions for which the photon energy is smaller each time.

In Figs. 4(c) and 4(d) we present the transition probability $W(z_i,\omega)$ for different magnetic fields, and for photon energies that satisfy $\Delta=\hbar\omega-\epsilon_g+E_b(z_i=16\,\text{Å})=0$ and $\Delta=\hbar\omega-\epsilon_g+E_b(z_i=32\,\text{Å})=0$, respectively. It is observed that as the magnetic field increases the transition probability is more intense, due to the higher magnetic confinement. In addition the behavior of the $W(z_i,\omega)$ as a function of the donor position is similar for all values of the magnetic field. Previous results for the transition probability $W(z_i,\omega)$ presented for superlattice 1, are similar to those found for superlattices 2 and 3.

The total absorption probability is shown in Fig. 5 as a function the photon energy. In Fig. 5(a) we present the total absorption probability, $W_T(\omega)$ for the superlattice 1, for different magnetic fields. We observe that there is a noticeable peak structure associated with impurities located at the center of the wells. It is important to mention that recently, Barbosa *et al.*[11] have found for the impurity-related optical absorption spectra in GaAs OW's with a magnetic field applied in the growth direction, two structures associated with impurities at the center and at the border of the heterostructure. Similar

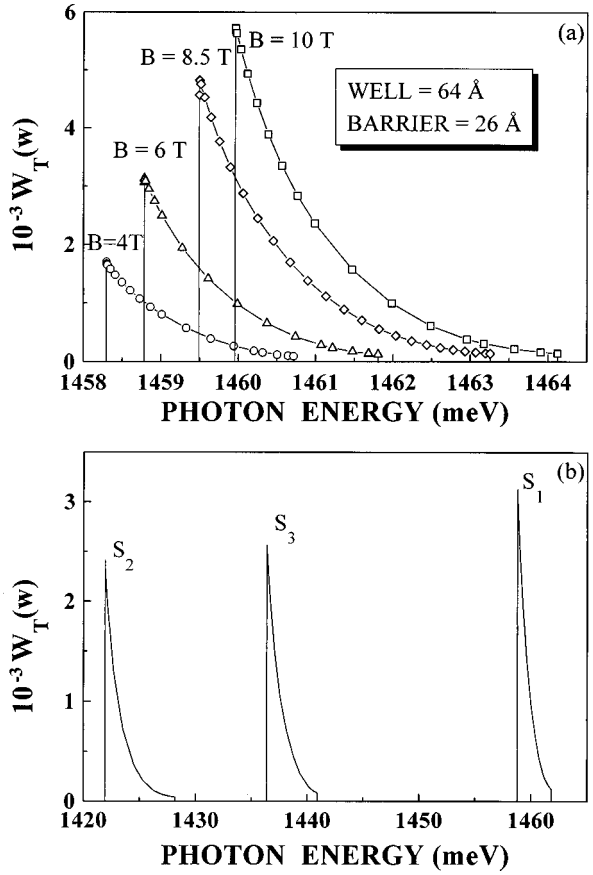

FIG. 5. Total optical absorption spectra [in units of W_0; see Eq. (21)] as a function of the photon energy $\hbar\omega$, for valence-to-donor transitions in GaAs-(Ga,Al)As superlattice. (a) A superlattice with well width=64 Å and barrier width=26 Å, for different fixed values of magnetic fields $B=4$, 6, 8.5, 10 T. (b) Superlattices reported by Skromme (see Table I) with a magnetic field $B=6$ T.

results were found for quantum wells,[7–9] quantum-well wires,[23] and quantum dots[21] without applied magnetic fields. However, in the present system we only have found one noticeable peak associated with impurities at the center of the wells, which is a consequence of the magnetotunneling due to the direction of the applied magnetic field. This is a very important difference to the previously cited results. In the range of the studied photon energies, the peak associated with impurities close to the barriers was only observed for low magnetic fields ($B=0.1$ T) and its intensity is despicable compared with the intensity of the peak associated with impurities at the center of the wells.

In Fig. 5(b) for a magnetic field $B=6$ T, we present the total absorption probability for the superlattices 1, 2, and 3, with well and barrier width similar to those reported by Skromme *et al.*[18] The behavior of $W_T(\omega)$ is equal for all superlattices, i.e., only a peak is present in the spectrum which is associated with impurities located at the center of the wells. In addition the photon energy range of the spectra increases with the well width.

The peak position in the total absorption probability, $W_T(\omega)$ as a function of the magnetic field for the superlattices reported by Skromme *et al.*[18] are shown in Fig. 6. Notice in Table I that for the superlattice 1 we have used for the donor acceptor and acceptor effective masses the values re-

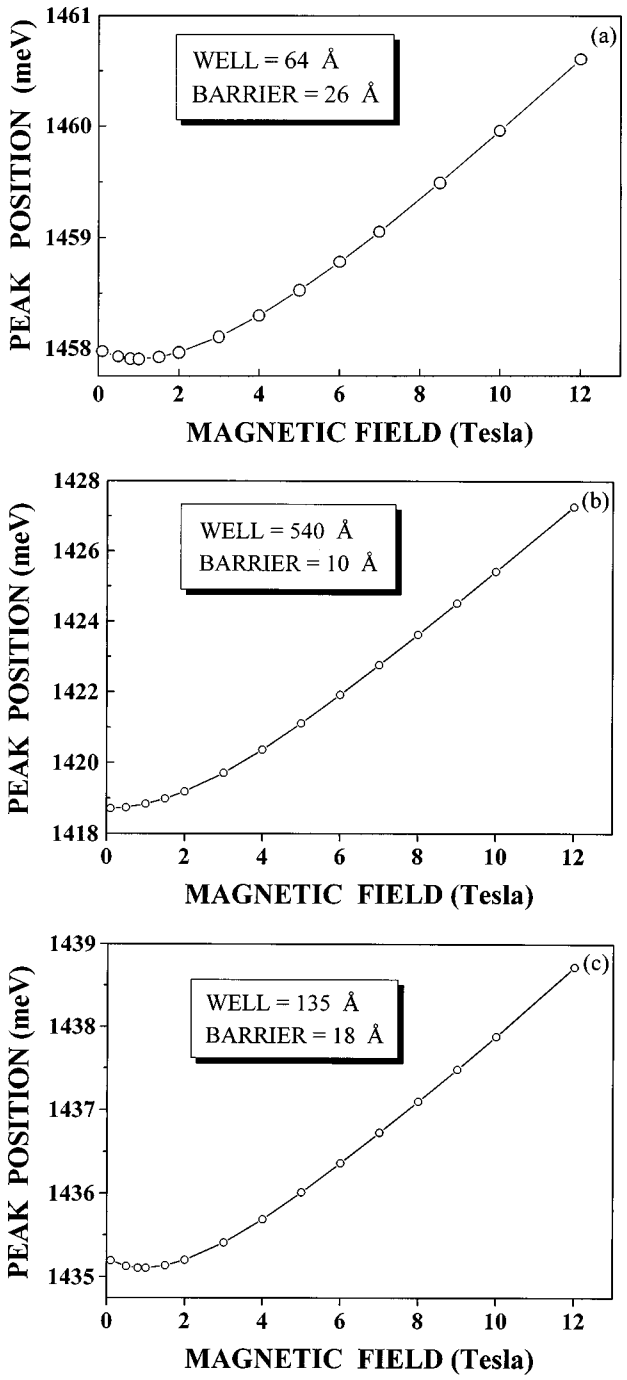

FIG. 6. Peak positions as a function of the magnetic field. (a) With well width=64 Å and barrier width=26 Å. (b) With well width=540 Å and barrier width=10 Å. (c) With well width =135 Å and barrier width=18 Å.

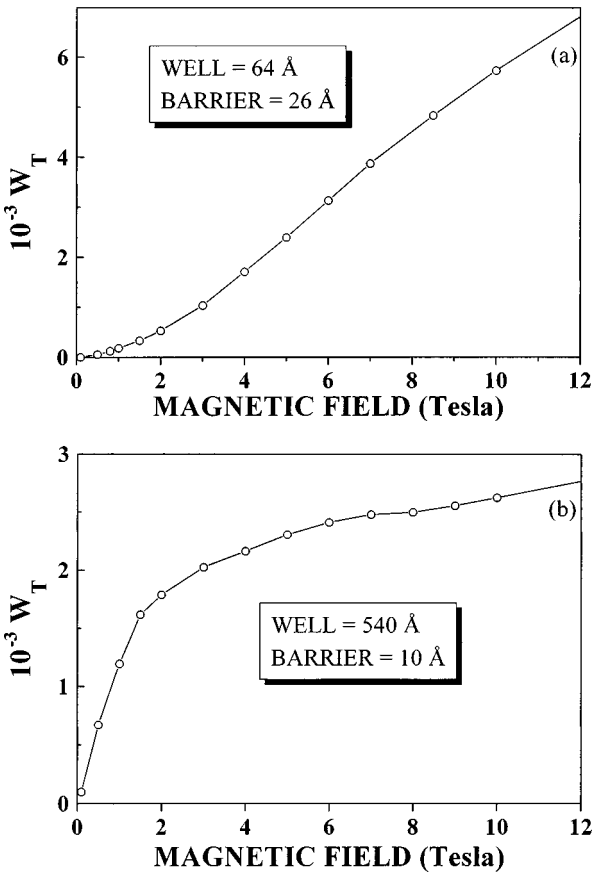

FIG. 7. Peak intensity of the total optical absorption spectra [in units of W_0; see Eq. (21)], as a function of the magnetic field, for valence-to-donor transitions in GaAs-(Ga,Al)As superlattices. (a) A superlattice with well width=64 Å and barrier width=26 Å. (b) With well width=540 Å and barrier width=10 Å.

ported in Refs. 12 and 13, different than those values used for superlattices 2 and 3. Despite this, in general we observed that the behavior is linear for magnetic fields larger that 4 T, due basically to the linear dependence of the magnetic levels with the applied magnetic field. This behavior is in qualitative agreement with magnetoluminescence results by Skromme *et al.*[18] for transitions between the conduction magnetic subband and the acceptor impurity states. We think that the no linear behavior of the peak position in energy for low magnetic fields is governed by the geometrical confinement, which is reflected in the donor binding energy, over the magnetic confinement.

The peak intensity of the total transition probability as a function of the magnetic field is displayed in Fig. 7. It is observed that the peak intensity increases with the applied magnetic field, due to the stronger magnetic confinement. For superlattices 1 and 3 the increment of the peak intensity is monotonous in the entire range of the magnetic field. However, we observed that for wider-well superlattices, the intensity increases rapidly for low magnetic fields, but looks similar to going to a saturation limit for higher magnetic fields.

IV. CONCLUSIONS

Summing up, we have calculated the optical-absorption spectra associated with transitions between the first Landau valence subband and the donor-impurity band in GaAs-(Ga,Al)As superlattices with in-plane magnetic fields. The donor-related magnetoabsorption spectra were calculated within the effective-mass approximation using a variational procedure and considering a homogeneous donor distribution in the superlattices. Electron and hole magnetic envelope wave functions were obtained by an expansion in terms of sine functions. We conclude that the binding energy decreases as the impurity approaches to the barrier for all mag-

netic fields. For impurities located at the center of the wells the binding energy always increases with the applied magnetic field. Essentially we found that the total absorption spectra under the action of applied magnetic fields present only a peak associated with transitions involving impurities at the center of the wells. This is a very important difference with respect to previous results in QW's, QWW's, and QD's, in which there have been found one structure associated with impurities located close to the center of these structures, and another related with on edge impurities. Also, we found that the energy position of the peak in the total absorption probability shows a linear dependence for magnetic fields larger that 4 T and that the intensity peak increases with the applied magnetic field. We estimate future interpretation of optical absorption spectra in GaAs-(Ga,Al)As superlattices under in-plane magnetic fields, must take into account these results.

ACKNOWLEDGMENTS

J. Silva-Valencia is grateful to the Mazda Foundation for Art and Sciences (Colombia). We thank L. E. Oliveira for valuable discussions and for a critical reading of the manuscript. This work was partially supported by the Colombian Scientific Agency (Colciencias) under the Grant Research Project No. 1106-05-025-96.

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