# Magnetoabsorption spectra of magnetoexciton transitions in GaAs/Ga$_{0.7}$Al$_{0.3}$As quantum wells

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The internal transitions and absorption spectra of confined magnetoexcitons in GaAs/Ga$_{0.7}$Al$_{0.3}$As quantum wells have been theoretically investigated under magnetic fields along the growth direction of the semiconductor heterostructure. The magnetoexciton states are obtained within the effective-mass approximation by using a variational procedure. The trial exciton-envelope wavefunctions are described as hydrogeniclike polynomial functions. The internal transition energies are investigated by studying the allowed magnetoexcitonic transitions using terahertz radiation circularly polarized in the plane of the quantum well. The intraexcitonic magnetoabsorption coefficients are obtained for transitions from $1s$-like to $2p^{\pm}$-like magnetoexciton states as functions of the applied magnetic field.

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In the last two decades, a considerable amount of experimental and theoretical studies have been devoted to the understanding of the optical properties of semiconductor heterostructures and nanostructures[1−14]. Such semiconductor systems are of significant importance for the development of electronic, optoelectronic, and spintronic devices. The study of exciton properties in those systems is of great importance, for example, coupled electron-hole (e-h) excitons, which arise from the e-h Coulomb interaction, may considerably modify the interband optoelectronic properties of semiconductor heterostructures[15,16]. For a number of reasons, heterostructures such as GaAs/Ga$_{1-x}$Al$_x$As superlattices, quantum wells (QWs), quantum wires (QWRs), and quantum dots (QDs) constitute the semiconductor systems that attract the most attention in the literatures. Studies in optical properties in this systems have been recently performed experimentally through photoluminescence (PL) and magnetoabsorption experiments and PL measurements of modulation-doped GaAs/AlGaAs QWs[7,11,17,18]. Experimental results have shown that excitons have discrete internal energy levels, behaving essentially as “atoms in semiconductors”, and the transition energies of excitons in semiconductor superlattices are found in the far-infrared or terahertz region. The terahertz dynamics of magnetoexcitons in GaAs/Ga$_{1-x}$Al$_x$As undoped multiple quantum wells (MQWs) under magnetic fields applied perpendicular to the well interface were investigated, and the resonant far-infrared absorption by the confined magnetoexciton was observed[3−6,19−24]. Moreover, within the effective-mass approximation, the magnetoexciton and magnetoabsorption have been investigated theoretically. A variational procedure was used to investigate the light-hole and heavy-hole magnetoexcitonic transition energies in GaAs/Ga$_{1-x}$Al$_x$As QWs. The exciton-envelope wavefunctions are described as products of electron and hole solutions of the associated QW potentials and symmetry adapted Gaussian functons[25,26]. Very recently, the effects of crossed electric and in-plane magnetic fields on the electronic and exciton properties in semiconductor heterostructures were investigated by this variational procedure[12,13].

The aim of this letter is to study the magnetoexciton transitions and magnetoabsorption spectra in single GaAs/Ga$_{0.7}$Al$_{0.3}$As QWs within a variational procedure in the effective-mass and parabolic band approximations. The trial wavefunctions for the exciton are orthogonalized variational wavefunctions which are associated with a set of hydrogeniclike polynomial functions[27,28]rather than Gaussian functions[25,29]. Exciton internal transitions are investigated by studying the allowed magnetoexcitonic transitions using far-infrared (terahertz) radiation circularly polarized in the plane of the QW. Intramagnetoexciton transition energies corresponding to excitations from $1s$-like to $2p^{\pm}$-like states are obtained. In addition, the magnetoabsorption coefficients corresponding to the intraexcitonic transition $1s \longrightarrow 2p^{\pm}$ are presented.

We consider exciton states in a GaAs QW of width $L$ surrounded by Ga$_{0.7}$Al$_{0.3}$As barriers in the presence of a magnetic field parallel to the growth direction. Within the effective-mass approximation, we assume a parabolic dispersion for electrons and a four-band model for holes, although, for simplicity, we discard the off-diagonal elements in the hole Hamiltonian, i.e., effects due to hole subband mixing are not included in the calculation. The values of the potential-well barriers $V_c$ and $V_v$ are determined from the Al concentration and assumed to be 60% and 40% of the total energy-band-gap discontinuity, respectively[27,28]. Moreover, for an exciton confined in a semiconductor QW, we take the exciton envelope wavefunction as proportional to $(\mathrm{e}^{\mathrm{i}\overrightarrow{K}\cdot\overrightarrow{R}}/\sqrt{S})\psi^{S}_{n,l,m,J_z^{\mathrm{e}},J_z^{\mathrm{h}}}(\overrightarrow{\rho},z_{\mathrm{e}},z_{\mathrm{h}})$, where $S$ is the transversal area of the QW, $\overrightarrow{K}$ is the exciton in-plane wave vector, $\overrightarrow{\rho}$ is the $xy$ relative coordinate, and $\overrightarrow{R}$ is the in-plane coordinate of the exciton center of mass. One may write

$$\psi^{S}_{n,l,m,J_z^{\mathrm{e}},J_z^{\mathrm{h}}}(\overrightarrow{\rho},z_{\mathrm{e}},z_{\mathrm{h}}) = f_{\mathrm{e}}(z_{\mathrm{e}})f_{\mathrm{h}}(z_{\mathrm{h}})\phi^{S}_{n,l,m}(\overrightarrow{\rho},z_{\mathrm{e}},z_{\mathrm{h}}), \quad (1)$$

where $f_{\mathrm{e}}$ and $f_{\mathrm{h}}$ are the $z$ parts of the QW electron and hole wavefunctions, respectively.

With energies measured with respect to the band gap of the GaAs bulk material expressed in units of Rydbergs ($R_0 = m_0 e^4/2\hbar^2$, where $m_0$ is the free-electron mass and $e$ is the proton charge), lengths in hydrogen Bohr radii ($a_0 = \hbar^2/m_0 e^2$), and magnetic fields in terms of the dimensionless quantity $\gamma = e\hbar B/2m_0 c R_0$. The heavy-hole ($J_z^{\mathrm{hh}} = \pm 3/2$) and light-hole ($J_z^{\mathrm{lh}} = \pm 1/2$) exciton Hamiltonians may be taken as[25]

$$\begin{aligned} H^{\mathrm{exc}}_{\pm 3/2} = & -\frac{m_0}{m_{\mathrm{e}}}\frac{\partial^2}{\partial z_{\mathrm{e}}^2} + V_c(z_{\mathrm{e}}) - \frac{m_0}{m_{\mathrm{h}}^{\pm 3/2}}\frac{\partial^2}{\partial z_{\mathrm{h}}^2} + V_v(z_{\mathrm{h}}) \\ & +(\gamma_1 + \gamma_2 + m_0/m_{\mathrm{e}})\Big( -\nabla^2_{\overrightarrow{\rho}} + \frac{\gamma^2\rho^2}{4}\Big) \\ & +(-\gamma_1 - \gamma_2 + m_0/m_{\mathrm{e}})\gamma L_z \pm \left(3\kappa + \frac{27}{4}q\right)\gamma \\ & -\frac{2}{|\mathbf{r}_{\mathrm{e}} - \mathbf{r}_{\mathrm{h}}|} \pm \frac{g_{\mathrm{e}}}{2}\gamma, \end{aligned} \tag{2}$$

$$\begin{aligned} H^{\mathrm{exc}}_{\pm 1/2} = & -\frac{m_0}{m_{\mathrm{e}}}\frac{\partial^2}{\partial z_{\mathrm{e}}^2} + V_c(z_{\mathrm{e}}) - \frac{m_0}{m_{\mathrm{h}}^{\pm 1/2}}\frac{\partial^2}{\partial z_{\mathrm{h}}^2} + V_v(z_{\mathrm{h}}) \\ & +(\gamma_1 + \gamma_2 + m_0/m_{\mathrm{e}})\Big( -\nabla^2_{\overrightarrow{\rho}} + \frac{\gamma^2\rho^2}{4}\Big) \\ & +(-\gamma_1 + \gamma_2 + m_0/m_{\mathrm{e}})\gamma L_z \pm \left(3\kappa + \frac{1}{4}q\right)\gamma \\ & -\frac{2}{|\mathbf{r}_{\mathrm{e}} - \mathbf{r}_{\mathrm{h}}|} \pm \frac{g_{\mathrm{e}}}{2}\gamma, \end{aligned} \tag{3}$$

with

$$L_z = \frac{\partial}{\mathrm{i}\partial\phi} \tag{4}$$

as the operator for the orbital angular momentum in the $z$ direction and

$$\nabla^2_{\overrightarrow{\rho}} = \frac{\partial^2}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2}{\partial\phi^2} \tag{5}$$

being the two-dimensional Laplacian in the QW plane. The GaAs conduction-band effective mass and dielectric constant are taken as $m_{\mathrm{e}} = 0.067m_0$ and $\varepsilon = 12.5$, respectively. The relevant mass parameters are

$$1/m_{\mathrm{h}}^{\pm 3/2} = \gamma_1 - 2\gamma_2, \tag{6}$$

$$1/m_{\mathrm{h}}^{\pm 1/2} = \gamma_1 + 2\gamma_2. \tag{7}$$

The Luttinger valence-band parameters are taken as $\gamma_1 = 7.36$, $\gamma_2 = 2.57$, $\kappa = 1.2$, $q = 0.04$, and the $g$ factor of the conduction-band electron as $g_{\mathrm{e}} = -0.44$. We consider orthogonalized variational wavefunctions in the $(n, l, m)$ states, i.e., we take[28]

$$\begin{aligned} \phi^S_{n,l,m}\ (\overrightarrow{\rho}, z_{\mathrm{e}}, z_{\mathrm{h}}) = & \left(-\frac{\gamma}{4}\rho^2\right)\rho^{|m|}\exp(-\mathrm{i}m\phi) \\ & \times P_{n,l,m}(r, \beta_{n,l,m})\exp(-\lambda_{n,l,m} r), \end{aligned} \tag{8}$$

where $P_{n,l,m}(r, \beta_{n,l,m})$, with $r = \sqrt{\rho^2 + (z_{\mathrm{e}} - z_{\mathrm{h}})^2}$, are hydrogeniclike polynomial functions for exciton states in which $\beta_{n,l,m}$ and $\lambda_{n,l,m}$ are variational parameters. Magnetoexciton energy states are labeled as $nlm(J_z^{\mathrm{e}}, J_z^{\mathrm{h}})$ which correspond to an $nlm$-like exciton state composed of a $J_z^{\mathrm{e}}(J_z^{\mathrm{e}} = \pm 1/2)$ electron and a $J_z^{\mathrm{h}}(J_z^{\mathrm{h}} = \pm 1/2, \pm 3/2)$ hole.

Once the states of the magnetoexcitons are known, the magnetoabsorption coefficient $\alpha(\omega)$ for intraexcitonic transitions from initial state $i$ to final state $f$ is essentially obtained by[26]

$$\begin{aligned} \alpha_{i\to f}(\omega) \propto \frac{1}{\omega}\Big| \Big\langle \psi^f_{n',l',m',J_z^{\mathrm{e}},J_z^{\mathrm{h}}}(\overrightarrow{\rho}, z_{\mathrm{e}}, z_{\mathrm{h}}) \Big| \widehat{\varepsilon} \\ \times \mathbf{P}_{\mathrm{r}} \Big| \psi^i_{n,l,m,J_z^{\mathrm{e}},J_z^{\mathrm{h}}}(\overrightarrow{\rho}, z_{\mathrm{e}}, z_{\mathrm{h}}) \Big\rangle \Big|^2 \\ \times\delta(E^f_{n',l',m',J_z^{\mathrm{e}},J_z^{\mathrm{h}}} - E^i_{n,l,m,J_z^{\mathrm{e}},J_z^{\mathrm{h}}} - \hbar\,\omega), \end{aligned} \tag{9}$$

where $\widehat{\varepsilon}$ corresponds to the photon polarization, and $\mathbf{P}_{\mathrm{r}}$ is the relative mechanical momentum of the e-h pair. By writing the relative mechanical momentum as $\mathbf{P}_{\mathrm{r}} = \mathbf{p}_{\mathrm{r}} + e/c\mathbf{A}_{\mathrm{r}}$, where $\mathbf{A}$ is the vector potential associated with the magnetic field $\mathbf{B} = B\widehat{z}$, and choosing the symmetric gauge, one finds

$$\widehat{\varepsilon}\cdot\mathbf{P}_{\mathrm{r}} = \frac{\hbar}{\sqrt{2}\mathrm{i}}\mathrm{e}^{\pm\mathrm{i}\phi}\left(\frac{\partial}{\partial\rho} \pm \frac{\mathrm{i}}{\rho}\frac{\partial}{\partial\phi} \mp \frac{Be}{2\hbar c}\rho\right), \tag{10}$$

here $\widehat{\varepsilon}$ corresponds to the right-hand side (or left-hand side) circularly polarized $\sigma^+$(or $\sigma^-$) in the QW plane.

The variational calculations have been performed for heavy-hole ($\mathrm{J}_z^{\mathrm{hh}} = \pm 3/2$) and light-hole ($\mathrm{J}_z^{\mathrm{lh}} = \pm 1/2$) magnetoexciton states in a 12.5-nm GaAs/$\mathrm{Ga_{0.7}Al_{0.3}As}$ QW. In our approach, the exciton envelope wavefunctions were described as the products of the variational hydrogeniclike wavefunctions and the electron and hole ground-state solutions of the effective-mass equation, along the $z$ axis for the barrier potentials of the GaAs/$\mathrm{Ga_{0.7}Al_{0.3}As}$ QW. This approach is different from the scheme which considers the magnetoexciton wavefunctions as products of Gaussian functions with appropriate hole and electron solutions of the potentials[25,26].

The growth-direction magnetic field dependence of the $1s$ and $2p^{\pm}$ light-hole and heavy-hole magnetoexciton variational energies are displayed in Fig. 1. The allowed $1s \longrightarrow 2p^{\pm}$ heavy-hole magnetoexciton transitions associated to the two optically active $1s(-1/2, -3/2)$ and $1s(+1/2, +3/2)$ magnetoexcitons are also shown in Fig. 1, for $\sigma^-$ and $\sigma^+$ circularly polarized far-infrared radiation in the GaAs/$\mathrm{Ga_{0.7}Al_{0.3}As}$ QW. It is shown that the allowed transition energies between different magnetoexciton states are found in the far-infrared or terahertz region (about 10 meV or 2.4 THz). With the increase of magnetic field, the energies of magnetoexciton rapidly increase. In the high magnetic field limit, when the Coulomb energy of the excitons may be viewed as a small perturbation on magnetic field effects, $\triangle m = +1$ transitions essentially correspond to the excitation of an electron from an electronic Landau level $n_{\mathrm{e}}$ to $n_{\mathrm{e}} + 1$, whereas $\triangle m = -1$ would be associated to the promotion of a hole from the Landau level $n_{\mathrm{h}}$ to $n_{\mathrm{h}} + 1$.

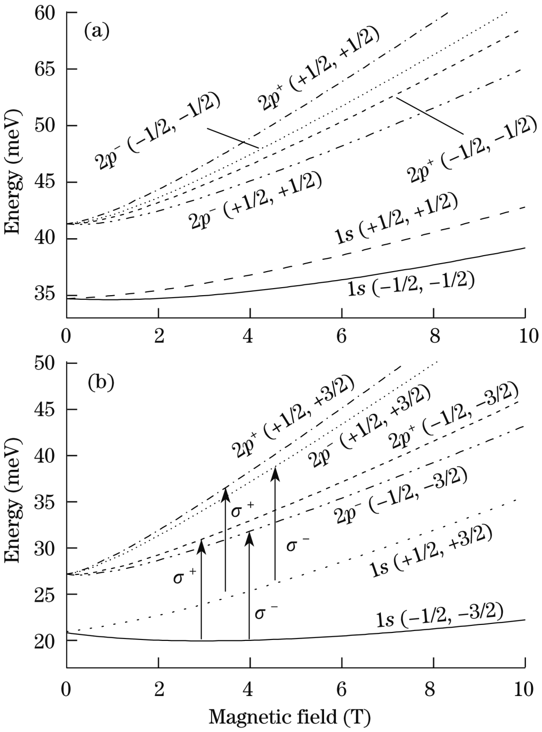

Fig. 1. Calculated variational energies of the $1s$ and $2p^{\pm}$ states of (a) light-hole and (b) heavy-hole magnetoexcitons as functions of the growth-direction applied magnetic field for a 12.5-nm GaAs/GaAlAs QW. Magnetoexciton energy states are labeled as $nlm(J_z^{\mathrm{e}}, J_z^{\mathrm{h}})$ which correspond to an $nlm$-like exciton state composed of a $J_z^{\mathrm{e}}$ electron (with $J_z^{\mathrm{e}} = \pm 1/2$). Spin-conserving magnetoexciton $1s \rightarrow 2p^{\pm}$ transition energies are shown with vertical arrows.

The energies corresponding to light-hole and heavy-hole $1s \longrightarrow 2p^{\pm}$ magnetoexciton transitions are shown in Fig. 2. For the allowed spin-conserving transitions, our results are in very good agreement with the results obtained by Duque *et al*[27]. and previous theoretical results[25]. With the increase of magnetic field, compared with the transition energy of light-hole, the transition energy of $1s \longrightarrow 2p^-(+1/2, +3/2)$ becomes equal to the transition energy of $1s \longrightarrow 2p^-(-1/2, -3/2)$. It indicates that the effect of magnetic field is dominant in the transition procedure for the heavy-hole magnetoexciton. Figure 3 displays the calculated light-hole and heavy-hole intraexcitonic magnetoabsorption coefficients, for $\sigma^-$ left- and $\sigma^+$ right-hand side circularly polarized lights in the QW plane. One can clearly see that the $\sigma^-$ left- and $\sigma^+$ right-oscillator strengths of the light-hole and heavy-hole $1s \longrightarrow 2p^{\pm}$ intraexcitonic transitions are of the same order of magnitude. This shows that both the light-hole and heavy-hole $1s \longrightarrow 2p^{\pm}$ intraexcitonic transitions should be observable in the measured spectra.

In summary, we have calculated the intramagnetoexciton transition energies corresponding to excitons from $1s$-like to $2p^{\pm}$-like magnetoexciton states in GaAs/Ga$_{0.7}$Al$_{0.3}$As QWs. The $\alpha(\omega)$ magnetoabsorption coefficients corresponding to the intraexcitonic $1s \longrightarrow 2p^{\pm}$ transitions are also presented, for the case of $\sigma^-$ left- and $\sigma^+$ right-hand side circularly polarized photons in the interface. Our results show that the higher energy experimental magnetoexciton transitions in the terahertz radiation correspond to light-hole $1s \rightarrow 2p$ magnetoexciton $\sigma^+$ transitions. The present calculations also indicate that the observed intraexcitonic transitions occur in both heavy-hole and light-hole magnetoexcitons.

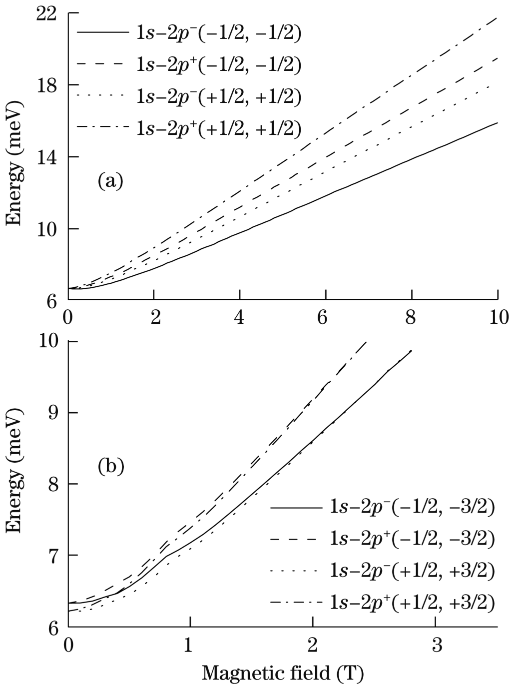

Fig. 2. (a) Light-hole and (b) heavy-hole spin-conserving $1s \rightarrow 2p^{\pm}$ transition energies in a 12.5-nm GaAs/GaAlAs as functions of the growth-direction applied magnetic field.

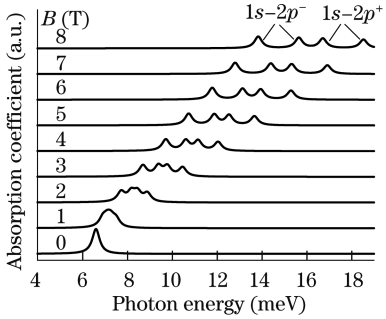

Fig. 3. Intraexcitonic light-hole and heavy-hole $1s \rightarrow 2p^{\pm}$ magnetoabsorption coefficients for the left- ($\sigma^-$) and right-hand ($\sigma^+$) circularly polarized light in the QW plane. The column of numbers on the left-hand side gives values of the applied magnetic field in T.

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