Excited states of shallow acceptors confined in GaAs/$Al_xGa_{1-x}As$ quantum wells

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An optical study of the excited states of shallow acceptors confined in narrow GaAs/$Al_xGa_{1-x}As$ quantum wells (QW's) is presented. The excited states have been investigated via the two-hole transitions (THT's) of the bound exciton recombination observed in selective photoluminescence (SPL) and photoluminescence excitation (PLE) spectroscopy. Several heavy-hole (hh) -like excited $nS(\Gamma_6)$ acceptor states dominate the satellite spectrum, but also the light-hole (lh) -like excited $2S(\Gamma_7)$ acceptor state has been observed in these SPL spectra. In addition, the THT corresponding to the parity-forbidden transition to the $2P_{3/2}$ excited state has been observed. When detecting any of the THT satellites corresponding to the $2S$ acceptor state, the $1S(\Gamma_6)$ hh-like acceptor ground state has been spectrally resolved from the $1S(\Gamma_7)$ lh-like acceptor state in PLE spectra. Together with the previously published results for the p-like excited states, these data complete the electronic structure of shallow acceptors in a QW.

I. INTRODUCTION

The upper valence band in bulk GaAs is p-like with a threefold degeneracy at the Γ point in the Brillouin zone and is consequently sixfold degenerate, if the spin is taken into account. Including also the spin-orbit interaction, these bands split into the $J=\frac{1}{2}$ and $J=\frac{3}{2}$ bands, with the fourfold degenerate $J=\frac{3}{2}$ band highest in energy at $\mathbf{k}=0$ in the bulk case. The upper $J=\frac{3}{2}$ band consists of the $m_J=\pm\frac{3}{2}$ heavy-hole (hh) and the $m_J=\pm\frac{1}{2}$ light-hole (lh) bands.

The shallow acceptor states are significantly more complex than the donor states, due to the more complicated nature of the valence band. For the case of a shallow effective-mass-like acceptor confined in a quantum well (QW), one has to take into account the mixing between the hh and lh bands. In a QW potential, the acceptor hh and lh levels are split even at $\mathbf{k}=0$, but mix at finite values of the in-plane $\mathbf{k}$ vectors. The mixing occurs for $\mathbf{k}$ vectors, which are of the same order as the reciprocal of the acceptor ground-state Bohr radius. Hence, the effect of valence-band mixing has to be taken into account for shallow acceptors in an effective-mass description.[1–5] In addition, since the acceptor binding energy exceeds the subband separation, a proper representation of the acceptor states must include Coulomb coupling between different subbands.[3] The resulting acceptor $1S$ ground state can be classified into two symmetry classes, similarly to the subbands: the Γ_6 hh-like and the Γ_7 lh-like acceptor states. We will maintain these notations, $1S(\Gamma_6)$ and $1S(\Gamma_7)$, although it is important to remember that this assignment to particular subbands is less appropriate for the acceptor $1S$ states. The hh-lh mixing is, in practice, significant for the two $1S$ acceptor states, maybe a 50-50 relation.[6] The energy separation between the $1S$ acceptor Γ_6 hh-like and the Γ_7 lh-like states is considerably reduced compared with the corresponding subband separation. For instance, for a 150-Å-wide QW, the hh-lh subband separation is 6.5 meV, while the corresponding $1S$ acceptor hh-lh splitting is predicted to be 0.5 meV.[3] This fact has recently been experimentally verified by magnetic-field-dependent and polarization-dependent excitation spectroscopy.[7]

The first calculations on the excited acceptor states including the effect of valence-band mixing were performed by Masselink, Chang, and Morkoç.[8,9] They used a multiband effective-mass approximation including the top four valence bands to calculate the Γ_6 hh-like and Γ_7 lh-like states of the acceptors at different positions in the QW. Subsequently, Pasquarello, Andreani, and Buczko[3] used a similar effective-mass model to calculate the excited acceptor states. The separation between the nth Γ_6 hh-like and Γ_7 lh-like excited states is predicted to asymptotically approach the hh-lh subband separation[3] with increasing value of n.

Pioneering experimental studies on the acceptors confined in GaAs/$Al_xGa_{1-x}As$ QW's were performed by Miller *et al.*[10] They observed $n=1$ electrons from the conduction band recombining with acceptor bound holes in a free-to-bound transition in photoluminescence (PL) spectra. The binding energies for the acceptor ground states were estimated as a function of the well width L_z.

For the case of acceptor excited states, most of the experimental work has been performed by partly far-infrared (FIR) spectroscopy and partly resonant Raman-scattering (RRS), selective PL (SPL), and PL excitation (PLE) spectroscopy. Different selection rules apply to these techniques. The acceptor excited states in center-doped QW's of widths in the range 100–200 Å were studied in FIR transmission,[11] in which only transitions between states of different parity are allowed. This means that the transitions from the s-like ground state to p-like excited states dominate the spectra. Several $2P$ states, $2P_{3/2}(\Gamma_8)$, $2P_{5/2}(\Gamma_8)$, and $2P_{5/2}(\Gamma_7)$, were observed in these FIR spectra. The S-like excited states were first investigated by RRS experiments.[12] In contrast to the FIR transmission measurements, transitions between states with the same parity are allowed in RRS experiments. Peaks interpreted as transitions to the $2S$ excited states were monitored for QW's of widths in the range 70–165 Å. Later on, S-like excited states have also been observed via two-hole transition (THT) of the bound exciton (BE), in which the confined acceptor is left in an excited S-like state. The $1S$-$2S$ acceptor transition energy was determined as a function of both the QW width[13] and of the position of the acceptor within the QW.[14]

We report in this paper a detailed study of the excited states of the shallow Be-acceptor confined in narrow $GaAs/Al_{0.3}Ga_{0.7}As$ QW's, which has been performed by means of selective photoluminescence (SPL) and photoluminescence excitation (PLE) spectroscopy. The acceptor electronic structure has been investigated via the exciton bound (BE) at the acceptor. Several acceptor excited states have been observed for the first time as two-hole transition (THT) satellites of the BE in the SPL spectra for QW's with different well width. In addition to the earlier reported transition from the acceptor $1S$ ground state to the excited $2S(\Gamma_6)$ state, we have in refined SPL measurements observed transitions to the excited $3S(\Gamma_6)$ state, the lh-like $2S(\Gamma_7)$ state and to the parity-forbidden $2P_{3/2}$ state. When the THT satellite is detected in a PLE spectrum, the splitting between the $1S(\Gamma_6)$ and $1S(\Gamma_7)$ acceptor ground state is observed. These results complete the experimental picture of shallow acceptor states in a QW from $1S(\Gamma_6)$ up to $3S(\Gamma_6)$.

II. SAMPLE PREPARATION AND EXPERIMENTAL CONDITIONS

The samples used in this study were grown by molecular-beam epitaxy on semi-insulating (100) GaAs substrates under As_4-rich conditions. The samples were grown at a temperature of nominally 680 °C and without interruptions at the QW interfaces. On top of the substrate, a 0.35-μm undoped GaAs buffer layer was grown. The structures investigated contained multiple QW structures with 50 periods of alternating layers of GaAs and $Al_xGa_{1-x}As$. The $Al_xGa_{1-x}As$ barriers were 150-Å wide with a height corresponding to an Al composition of $x=0.30$. The samples used in this study were selectively doped with Be acceptors in the central 20% of the QW's. The Be concentration has been varied in a wide range, but the spectra shown in this paper are measured on samples with a concentration of 3×10^{16} to 1×10^{17} cm^{-3}.

For the SPL and PLE measurements an Ar^+ ion laser was used to pump a Titanium-doped Sapphire solid-state laser. The emitted light from the samples, perpendicular to the incident laser beam, was focused on the slits of a 1-m double-grating monochromator and detected with a dry-ice-cooled GaAs photomultiplier.

III. SELECTIVE PHOTOLUMINESCENCE RESULTS

The PL spectra with above-band-gap excitation for these samples measured at low temperatures are completely dominated by the free exciton (FE) and the acceptor bound exciton (BE) as illustrated in Fig. 1 for a 150-Å-wide QW, doped in the central 30 Å to a level of 3×10^{16} cm^{-3}. At high excitation conditions, the biexciton is also observed 1.0 meV below the FE.[15,16] At above-band-gap excitation, usually no additional satellite features are detectable. The method commonly used in bulk material to enhance the THT satellites is by exciting resonantly with the acceptor BE, since the satellites can be regarded as a generalized form of BE recombination. The same method is shown to be also applicable to QW's, in which an enhancement of the THT satellites can be achieved by excitation resonant with either any of the FE states or the BE state.[13] In case of excitation close to or resonant with the acceptor BE, an additional satellite originating from a resonant Raman-scattering (RRS) process appears in the spectrum.[13] An example of a satellite spectrum, when the excitation is resonant with the acceptor BE, is shown in Fig. 2 for a 140-Å-wide QW doped to a level of 5×10^{16} cm^{-3} in the central 28 Å. This satellite spectrum partly overlaps with the GaAs bulk spectrum. However, the GaAs spectrum can easily be distinguished from the QW-related spectrum by excitation at energies well below the QW transition energy. The THT peak corresponding to the $2S(\Gamma_6)$ acceptor transition dominates by far the satellite spectrum, but a weak feature due to a transition to the next S-like state, the $3S(\Gamma_6)$ state, also appears weakly as a satellite (Fig. 2). The energy positions derived from the THT experiments for the different states of an acceptor confined in the center of a 150-Å-wide QW are given in Fig. 3. An additional THT satellite, interpreted as due to the "forbidden" transition to the $2P_{3/2}$ state, is observed in this SPL spectrum. There is no proper theoretical approach on the selection rules applicable to THT's published up to now, to the

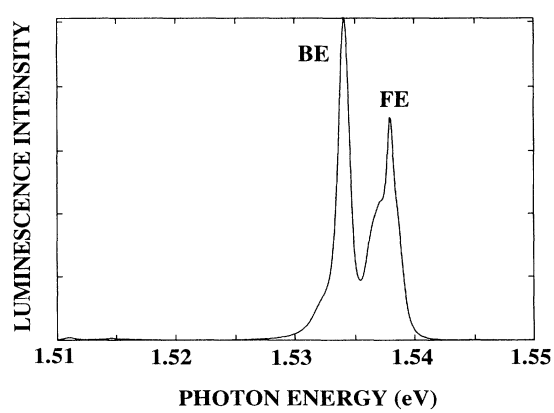

FIG. 1. PL spectrum of an acceptor-doped 150-Å-wide QW measured at 1.6 K with excitation at 1.652 eV. The FE and acceptor BE dominate this PL spectrum, but the biexciton is also observed 1.0 meV below the FE. The intensity of the biexciton versus FE increases with increasing excitation intensity.

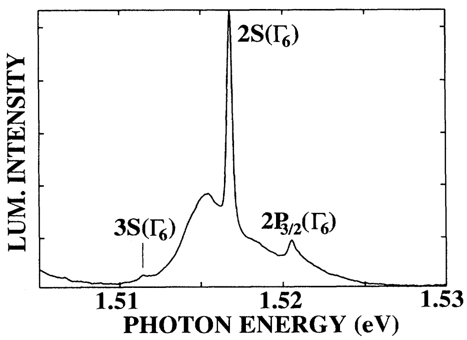

FIG. 2. SPL spectrum of a 140-Å-wide QW doped to a level of 5×10^{16} cm^{-3} in the central 28 Å. The SPL spectrum is measured at 1.6 K with the excitation resonant with the acceptor BE. The THT satellite corresponding to the $1S(\Gamma_6)$-$2S(\Gamma_6)$ acceptor transition, denoted $2S(\Gamma_6)$ in the figure, dominates this SPL spectrum, but a weak feature due to the transition to the next S-like state, the $3S(\Gamma_6)$ state, is also observed. In addition, a THT peak originating from the parity-forbidden $1S(\Gamma_6)$-$2P_{3/2}$ acceptor transition is monitored.

best of our knowledge. This means that no guidance is derived from the theory, but the knowledge we have about these transitions is deduced from experimental considerations. For the case of shallow acceptors in bulk GaAs, THT peaks corresponding to transitions to excited $nS_{3/2}$ states dominate the SPL spectra, while no THT satellite related to the transition to the $P_{3/2}$ state is detected. However, a feature related to the $P_{3/2}$ state is observed for the donor acceptor pair (DAP) transition.[17] For DAP recombinations, the symmetry is reduced and the selection rules are accordingly expected to be relaxed. Also, when going from bulk to a QW, the symmetry is reduced: From T_d for a substitutional acceptor in bulk to D_{2d} for an acceptor in the center of a QW. Accordingly, the THT selection rules are expected to be relaxed also for the case of QW transitions. The transition energy derived for the $1S_{3/2}$-$2P_{3/2}$ transition, 18.5 meV, in these SPL measurements is found to be in excellent agreement with the result, 18.6 meV, obtained for a 150-Å-wide QW in FIR-absorption spectra.[11] In FIR absorption, transitions to P-like excited states dominate the spectra. The $1S_{3/2}$-$2P_{5/2}$ transitions are found to be the strongest in FIR spectra for Be-doped QW's,[11] while the $1S_{3/2}$-$2P_{3/2}$ transition is barely monitored for well widths as small as 150 Å. In addition, despite the fact that the $2P_{3/2}$ THT satellite exhibits the largest half-width, $\Delta_{\rm FWHM}\approx0.5$ meV (where FWHM denotes full width at half maximum), among the THT satellites observed in the SPL spectrum, the estimate of the $1S_{3/2}$-$2P_{3/2}$ transition energy is significantly more accurate in these THT experiments with a half-width about half as large as that observed in FIR-absorption measurements.

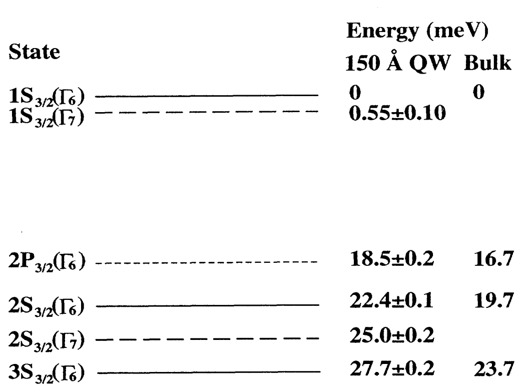

FIG. 3. The electronic structure for a central acceptor confined in a 150-Å-wide QW as deduced from THT studies of the acceptor BE.

The observation of the THT satellites in SPL spectra opens also the possibility of monitoring the acceptor BE in PLE spectra. This fact is illustrated in Fig. 4 showing PLE spectra for the same 150-Å-wide QW as that used in Fig. 1. If the detection energy is close to any of the THT peaks, the BE peak appears in the PLE spectrum in addition to the usually observed FE$^{\rm hh}$ and FE$^{\rm lh}$ peaks. The PLE spectrum, when the strongest THT peak—the $2S(\Gamma_6)$—is resonantly detected, is of particular interest (see Fig. 4). A doublet structure of the acceptor BE peak is then observed. The splitting between the two components measures to 0.55 meV for the 150-Å-wide QW and is found to increase with decreasing QW width.[7] These two components exhibit a pronounced thermalization behavior, consistent with a splitting originating from the initial acceptor ground state. This doublet structure has been studied in a separate investigation[7] and is interpreted as the $1S(\Gamma_6)$ hh and $1S(\Gamma_7)$ lh states of the acceptor ground state. This interpretation has been confirmed by polarized PLE measurements and also luminescence and PLE experiments in the presence of a magnetic field. Furthermore, a similar splitting of the $2S_{3/2}$ THT component can be resolved in SPL spectra as shown in Fig. 5, if the excitation is resonant with either the acceptor $1S(\Gamma_6)$ or $1S(\Gamma_7)$ ground state.[7] These satellite states are hereafter referred to as the $2S(\Gamma_6)[1S(\Gamma_6)]$ and $2S(\Gamma_6)[1S(\Gamma_7)]$ states, respectively. The energy splitting between the satellite components in the SPL spectra is the same as that observed in PLE spectra and originates from the different initial state in the THT process, either the acceptor $1S(\Gamma_6)$ hh or $1S(\Gamma_7)$ lh ground state. This behavior is illustrated in Fig. 5. In the lower spectrum, the BE of the acceptor hh ground state, $1S(\Gamma_6)$, is resonantly excited and the satellite peak, $2S(\Gamma_6)[1S(\Gamma_6)]$ corresponding to the $1S(\Gamma_6)$-$2S(\Gamma_6)$ transition dominates the SPL spectrum (Fig. 5). If the excitation energy is slightly upshifted, to be resonant with the BE of the acceptor lh state, $1S(\Gamma_7)$, a second THT satellite, $2S(\Gamma_6)[1S(\Gamma_7)]$, appears on the high-energy side of the $2S(\Gamma_6)[1S(\Gamma_6)]$ peak (Fig. 5) with an energy separation corresponding to the differences in energy between the acceptor $1S(\Gamma_6)$ hh and $1S(\Gamma_7)$ lh states. The low-energy component $2S(\Gamma_6)[1S(\Gamma_6)]$ is due to a relaxation process from the

$1S(\Gamma_7)$ state to the $1S(\Gamma_6)$ state preceding the $1S(\Gamma_6)-2S(\Gamma_6)$ scattering process. As seen in Fig. 5, the intensity of the high-energy $1S(\Gamma_7)$-related THT satellite, $2S(\Gamma_6)[1S(\Gamma_7)]$, never exceeds the intensity of the $2S(\Gamma_6)[1S(\Gamma_6)]$ satellite even at excitation resonant with the acceptor $1S(\Gamma_7)$ BE state. An almost identical behavior, although at a significantly lower intensity level, is observed for the next $3S_{3/2}$ THT satellites (Fig. 5). This fact is an important point in order to distinguish between excited states of different origin as will be further unfolded for the next THT satellite observed, $2S(\Gamma_7)[1S(\Gamma_7)]$ displaced 25.0 meV from the excitation energy. This satellite is almost undetectable upon excitation resonant with the $1S(\Gamma_6)$ acceptor BE state, while it is strongly enhanced, when the excitation is shifted to resonance with the $1S(\Gamma_7)$ acceptor BE peak. This behavior is in striking contrast with what is observed for the $2S(\Gamma_6)$ and $3S(\Gamma_6)$ satellites as obvious in Fig. 5. Accordingly, the $2S(\Gamma_7)[1S(\Gamma_7)]$ THT satellite [denoted $2S(\Gamma_7)$ in Fig. 5] is interpreted as the transition to the lh-like $2S(\Gamma_7)$ excited state.

To summarize, we have observed THT satellites for a 150-Å-wide QW in SPL spectra corresponding to transitions involving several acceptor excited states: $2P_{3/2}$, $2S(\Gamma_6)$, $2S(\Gamma_7)$, and $3S(\Gamma_6)$. In addition, the hh and lh acceptor ground states, $1S(\Gamma_6)$ and $1S(\Gamma_7)$, respectively, have been resolved in SPL and PLE spectra. The acceptor transition energies determined from the energy displacement of the THT satellite versus the principal BE observed in SPL spectra are summarized for different well widths and compared with corresponding transition energies in bulk GaAs in Table I.

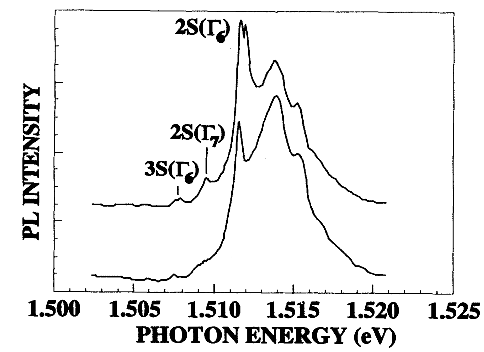

FIG. 5. Two SPL spectra with the excitation resonant with the acceptor BE related to the acceptor hh ground state (the lower spectrum) and the acceptor lh state (the upper spectrum), respectively. In the lower spectrum, only the THT satellites corresponding to the $1S(\Gamma_6)$-$2S(\Gamma_6)$ and $1S(\Gamma_6)$-$3S(\Gamma_6)$ acceptor transitions, denoted $2S(\Gamma_6)$ and $3S(\Gamma_6)$ in the figure, are observed. When the excitation is upshifted to be resonant with the lh state (the upper spectrum), the $2S(\Gamma_6)$ and $3S(\Gamma_6)$ single satellite lines are replaced by doublet satellites corresponding to two different initial states, $1S(\Gamma_6)$ or $1S(\Gamma_7)$, respectively. The satellite denoted $2S(\Gamma_7)$ in the figure, on the other hand, appears just in case of excitation resonant with the $1S(\Gamma_7)$ state and is therefore interpreted as the transition to the first excited acceptor lh state, $2S(\Gamma_7)$.

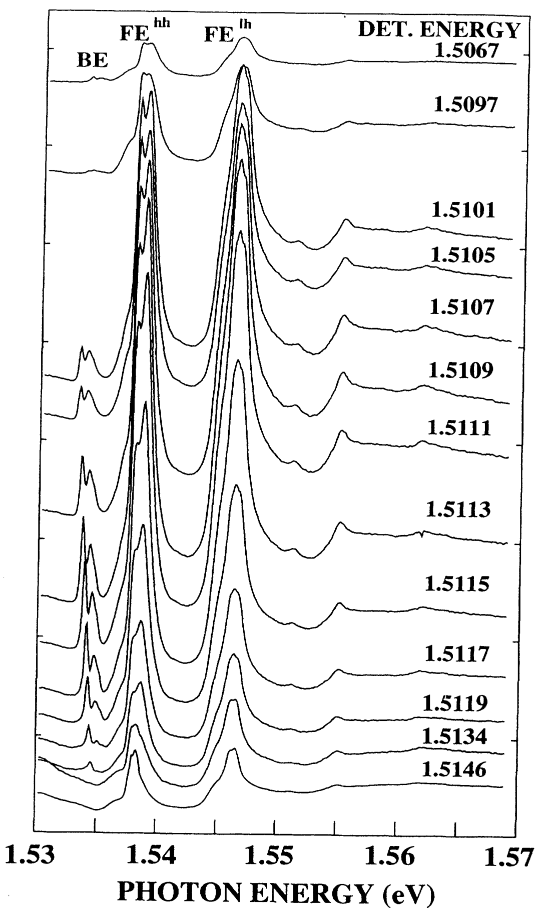

FIG. 4. A synopsis of PLE spectra for the same QW structure as that used in Fig. 1. The detection has been close to or resonant with the strongest THT satellite (at 1.5113 eV) corresponding to the $1S(\Gamma_6)$-$2S(\Gamma_6)$ acceptor transition. In addition to the dominating hh and lh states of the FE, a doublet structure due to the acceptor BE is observed. This doublet structure exhibits a pronounced thermalization behavior at increasing temperatures, which implies that the splitting originates from the initial state, the acceptor ground state, in the BE excitation process. Accordingly, the doublet structure is interpreted as being due to the splitting between the hh and lh state of the acceptor $1S$ ground state.

IV. DISCUSSION

When the acceptor BE recombines, the acceptor is normally left in its $1S$ ground state after the recombination. However, there is a small, but nonzero probability, that the acceptor instead is left in an excited state after recombination. These possible recombination processes with the different final states are illustrated in Fig. 6. The first recombination process, when the acceptor is left in its ground state, is denoted the principle BE recombination in Fig. 6, while the second case with the acceptor left in

TABLE I. The energy positions for different acceptor states relatively the acceptor $1S(\Gamma_6)$ ground state in QW's of varying well widths estimated from the energy positions of the THT satellites in SPL spectra and compared with theoretical predictions by Fraizzoli and Pasquarello (Ref. 20). The experimental results for the Be acceptor in bulk GaAs are derived from Ref. 17.

	50 Å		69 Å		94 Å		150 Å		GaAs
	Expt.	Theory	Expt.	Theory	Expt.	Theory	Expt.	Theory	Expt.
$1S_{3/2}(\Gamma_7)$					0.65±0.10	1.0	0.55±0.10	0.5	
$2P_{3/2}$					(19.9±0.2)	19.6	18.5±0.2[a]	17.0	16.7
$2S_{3/2}(\Gamma_6)$	31±1	30.2	28.5±0.5	27.1	24.4±0.2	24.4	22.4±0.1	21.9	19.7
$2S_{3/2}(\Gamma_7)$							25.0±0.1	24.4	
$3S_{3/2}(\Gamma_6)$			37.0±0.5	33.8	30.2±0.3	30.7	27.7±0.1	27.0	23.7

[a] $L_z = 140$ Å.

an excited state after recombination is referred to as the two-hole transition (THT) (Fig. 6). In the PL spectrum, there is a constant energy separation between the BE and the THT peaks corresponding to the energy needed to excite the acceptor from the ground state to an excited state. Since the THT peaks are usually weak and below the detection limit at excitation above the band gap, selective excitation is a way to enhance the THT peaks and accordingly to identify the peaks. While such THT peaks are commonly observed in bulk material,[18] to our knowledge the first report on THT in QW's was not published until a few years ago.[19] In addition to the observation of the THT transitions in SPL spectra, the same acceptor transitions have been observed in resonant Raman scattering RRS.[13,19]

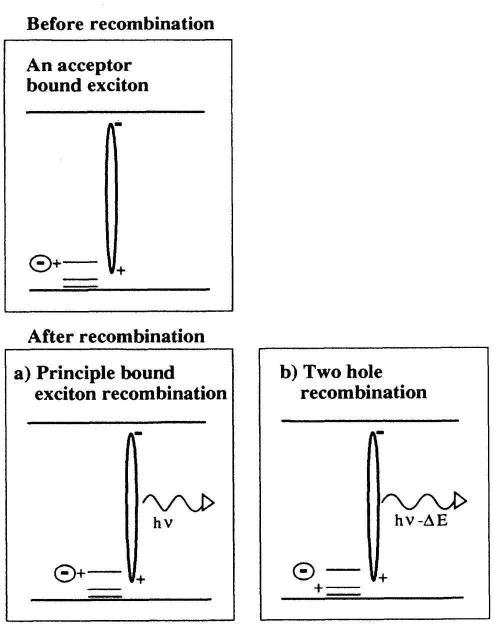

FIG. 6. Illustration of different BE recombinations. The upper figure shows an acceptor BE before the recombination. After the recombination, the acceptor hole is normally left in its $1S$ ground state and a photon of energy $h\nu$ has been emitted as illustrated in the lower figure (a). However, there is a small, but nonzero probability that the acceptor is instead left in an excited nS state after the recombination (b). This is experimentally observed as a reduction of the emitted photon energy to $h\nu-\Delta E$, where ΔE corresponds the energy needed to excite the acceptor to the nS state.

Up to now, no publication has properly addressed the issue of the theoretical treatment of two-particle transitions (TPT's) for BE's in QW's: Two-electron transitions for donor BE's or two-hole transitions (THT's) for acceptor BE's. Thus, we provide no guidance from the theory about the selection rules applicable for TPT's. Instead, empirical considerations, such as comparisons with other experimental techniques and results, are usually referred to in order to deduce the selection rules. For the case studied here, i.e., acceptors confined in GaAs/$Al_xGa_{1-x}As$ QW's, it has in earlier investigations been concluded that THT's corresponding to transitions to S-like excited states dominate the satellite spectrum.[13,14] This conclusion is supported by the fact that the same acceptor transitions are observed via both the THT satellites and the resonant Raman scattering (RRS). With the excitation resonant with the FE, the THT satellites dominate in the SPL spectrum, while the RRS peaks are strongest when the excitation is close to or resonant with the acceptor BE. RRS transitions between states with the same parity are allowed, i.e., transitions to S-like excited states are allowed from the acceptor $1S$ ground state. This interpretation is also consistent with the case of acceptors in bulk GaAs, for which THT's associated with transitions to S-like excited states dominate the satellite spectrum, while P-like excited states have been monitored in lower symmetry DAP transitions.[17] The selection rules applicable to the THT's have been explained in terms of a direct process,[18] in which the wave function of the initial BE state has a contribution from the final-state wave function of different like particles: $1S$, $2S$, and so on. In this description, the THT satellite intensity reflects then the proportion of each final-state wave function in the wave function of the initial BE state.

However, in the case of acceptors in QW's, the symmetry is reduced to D_{2d} for a central acceptor from T_d for an acceptor in bulk GaAs. This means that the selection rules applicable are further relaxed, similarly to the DAP transitions in the bulk GaAs case. Accordingly, it is not surprising that the parity-forbidden transition to the $2P_{3/2}$ state is observed in these transitions in the QW.

The acceptor ground state, $1S_{3/2}(\Gamma_8)$, in bulk GaAs splits into two doublet states in a QW, similarly to the upper valence band: A more strongly bound state,

$1S_{3/2}(\Gamma_6)$, of dominating hh character and another state, $1S_{3/2}(\Gamma_7)$, associated mainly with the lh subbands. As already mentioned in the Introduction, these acceptor states are strongly mixed states. The theoretical approaches on the acceptor electronic structure reported are based on the effective-mass theory[3,5,8,20] or the effective tight-binding model.[4] From these calculations, it is deduced that the splitting between the acceptor $1S_{3/2}(\Gamma_6)$ and $1S_{3/2}(\Gamma_7)$ states increases with decreasing QW width (down to $L_z=50$ Å).[20] Also, the splitting between the acceptor $1S_{3/2}(\Gamma_6)$ and $1S_{3/2}(\Gamma_7)$ ground states is considerably less than the corresponding separation between the hh and lh subbands. However, for the corresponding acceptor excited states, the splitting increases asymptotically towards the subband splitting. For instance, for a 150-Å-wide QW, we have measured a ground-state splitting of 0.55 meV between the acceptor $1S_{3/2}(\Gamma_6)$ and $1S_{3/2}(\Gamma_7)$ states, while the corresponding splitting for the excited $2S$ states is measured to 2.6 meV (Table I). These derived values on the acceptor splittings should be compared with a hh-lh subband separation of 6.5 meV, estimated from the separation between the hh-FE and lh-FE states. The difference between the hh and lh FE binding energies is deduced from the FE $1S$-$2S$ energy separations observed in the PLE measurements for the hh and lh states, respectively.

The experimentally determined energy separations for the acceptor hh and lh states should be compared with the theoretically predicted acceptor splittings. Fraizzoli and Pasquarello have calculated the energy separation between the $1S(\Gamma_6)$ and $1S(\Gamma_7)$ states to be 0.5 meV,[20] while the corresponding separation for the excited $2S$ states is predicted to be 2.5 meV. Accordingly, there is an excellent agreement between the theoretically predicted and our experimentally determined values for the energy separations between the hh-like Γ_6 and lh-like Γ_7 acceptor states, both for the $1S$ ground state and the excited $2S$ excited state.

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