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# Spectroscopy of a high-mobility GaAs-$Ga_{1-x}Al_xAs$ one-side-modulation-doped quantum well

M. H. Meynadier, J. Orgonasi, C. Delalande, J. A. Brum, G. Bastard, and M. Voos
*Groupe de Physique des Solides de l'Ecole Normale Supérieure, 24 rue Lhomond F-75005 Paris, France*

G. Weimann and W. Schlapp
*Forschungsinstitut der Deutschen Bundespost, D-6100 Darmstadt, Federal Republic of Germany*

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We report the results of low-temperature photoluminescence and photoluminescence excitation spectroscopy experiments performed on a 150-Å-thick GaAs-$Ga_{0.61}Al_{0.39}As$ one-side-modulation-doped quantum well. An interpretation of the excitation and luminescence spectra has been obtained, yielding a GaAs band-gap renormalization of 19 meV for an areal electron concentration of $4.5\times10^{11}$ cm$^{-2}$.

## I. INTRODUCTION

The modulation-doped GaAs-$Ga_{1-x}Al_xAs$ quantum wells have been far less studied than either the single heterojunctions or the undoped quantum wells. This may be due to the systematically low carrier mobilities exhibited by the symmetrically doped wells and attributed to the poor quality of the inverted interface (i.e., GaAs grown on top of $Ga_{1-x}Al_xAs$).[1] Optical studies were performed on nominally symmetrically doped quantum wells with relatively low mobilities and/or thick GaAs layers.[2,3] A common trend to the interpretation of these optical results is the need for using a renormalized GaAs band gap due to electron-electron and electron-hole exchange and correlation effects. These effects were recently evaluated and discussed.[4–9] Very recently, Chaves *et al.*[10] have reported a novel charge-transfer effect which takes place in a single asymmetric quantum well.

We report in this paper the results of photoluminescence excitation spectroscopy performed at low temperature on *one-side*-modulation-doped quantum wells. The advantages of such structures over the wells which are modulation-doped on either side is that high electron mobilities can be achieved[11] owing to (i) the larger spatial separation achieved between the quasi-bidimensional electron gas and the inverted interface and (ii) the absence of deleterious Si segregation and/or in-well diffusion which apparently take place when one attempts to dope the inverted interface. One of our goals was to check whether it is possible to reasonably account for the observed optical features by means of band-to-band transitions and, if not, to obtain an estimate of excitonic and/or band-gap renormalization effects in quantum wells containing high mobility electrons.

## II. EXPERIMENTAL RESULTS

The sample used in the present experiments has been grown by molecular-beam epitaxy. It is a one-side-modulation-doped 150-Å-thick GaAs quantum well clad between $Ga_{0.61}Al_{0.39}As$ barriers. The actual structure consists in a semi-insulating GaAs substrate followed by a 2.5-$\mu$m-thick GaAs buffer layer, a GaAs-$Ga_{0.61}Al_{0.39}As$ superlattice ($7\times35$ Å$+8\times100$ Å), the 15 nm thick GaAs quantum well, all the layers being nominally undoped. The quantum well was topped by a 30-nm-thick $Ga_{0.61}Al_{0.39}As$ undoped spacer followed by a 33-nm Si-doped ($N_d=10^{18}$ cm$^{-3}$) $Ga_{0.61}Al_{0.39}As$ layer. Finally a 25-nm-thick GaAs cap layer was grown on top of the overall structure. The purpose of the undoped GaAlAs-GaAs superlattice was to improve the quality of the bottom interface. The growth sequence is shown in the upper part of Fig. 1 which displays the band-edge profile of the investigated heterostructure.

The carrier density in the quantum well was determined by Hall and Shubnikov–de Haas measurements to be $2.9\times10^{11}$ cm$^{-2}$ at low temperature (1.7 K) in the dark and $4.5\times10^{11}$ cm$^{-2}$ under illumination, in the conditions where the optical experiments have been performed. The later quantity, which will be used in the rest of the paper

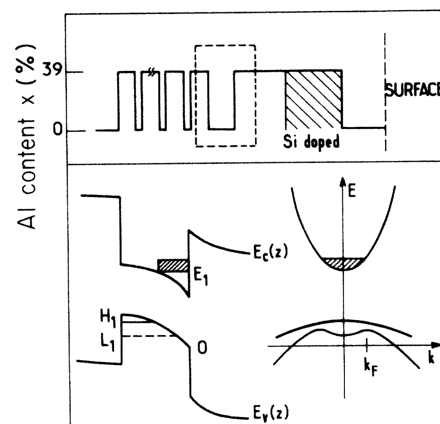


FIG. 1. Upper part: Aluminum concentration profile of the investigated structure. Lower part: Band-edge profiles in the vicinity of the doped well (left panel); schematic in-plane dispersion relations (right panel).

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corresponds to a Fermi energy of 16.1 meV measured from the ground electron subband $E_1$ if the GaAs electron effective mass is taken as $0.07m_0$. The carrier mobility in the dark is $2.1\times10^5$ $cm^2/V\,s$ (Ref. 7) at $T=4.2$ K. Figure 2 shows the excitation spectrum of the 150-Å-thick GaAs well luminescence, recorded at 1516 meV by tuning a LD 700 cw dye laser. The spectrum exhibits several broad lines and at least an extremely sharp one ($\delta$) at 1553 meV which remains unidentified according to our interpretation.

The luminescence spectrum of the sample is shown on the left-hand side of Fig. 2. The exciting light (1550 meV) is below the $Ga_{0.61}Al_{0.39}As$ band gap. Thus the luminescence arises from the 150-Å-thick GaAs well as well as from the buffer layer. In fact, the structure appearing on the low-energy side of the photoluminescences can be proved, using excitation spectroscopy, to originate from the GaAs buffer layer. The main peak contains both the buffer and quantum-well luminescences, the low-energy side being essentially due to the buffer and the high-energy side to the quantum well. The precise location of the quantum-well luminescence peak has been obtained by extrapolating magneto-luminescence experiments, where the quantum well and buffer luminescences are resolved.[12] The energy distance separating the luminescence peak from the lowest-lying peak in the excitation spectrum is 18 meV.

When the power of the incident light is increased over 4 orders of magnitude the peak in the luminescence band is slightly blue-shifted ($\sim3$ meV) while a high-energy tail develops. Moreover, a shoulder appears on this high-energy tail, approximately located 13 meV above the energy of the luminescence peak (Fig. 3).

Finally we have noticed that the sample was slightly inhomogeneous. By varying the laser spot by steps of 1 mm, a global shift of about 3 to 4 meV was found of both the photoluminescence and excitation spectra.

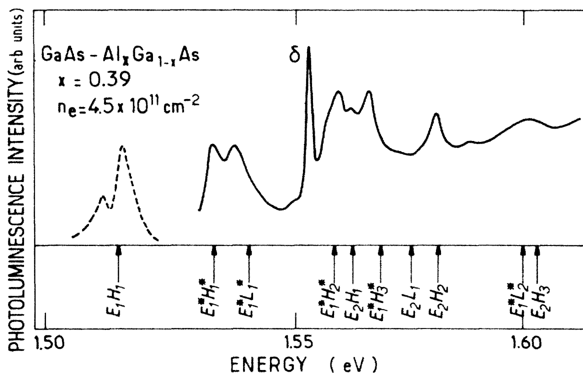


FIG. 2. Photoluminescence (dashed line) and excitation spectrum (solid line) of the investigated quantum well. The lower part of the figure indicates the calculated energies of the various subband-to-subband transitions accounting for a 19-meV band-gap renormalization. The transitions without asterisks occur at $k_\perp=0$, the ones with asterisks at $k_\perp=k_F$.

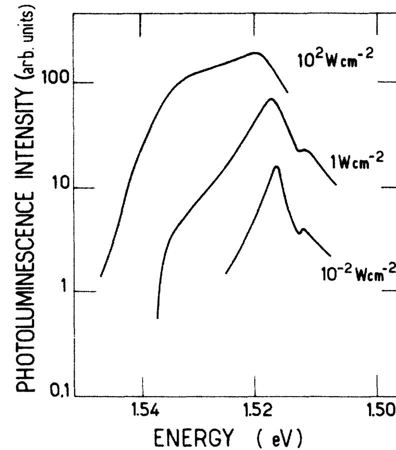


FIG. 3. Photoluminescence band of the asymmetrically doped quantum well versus photon energy for three different intensities of the exciting laser light (semilogarithmic scale).

## III. ENERGY LEVELS IN ONE-SIDE-MODULATION-DOPED QUANTUM WELLS

The energy-level calculations have been performed in the Hartree approximation. Since $L=150$ Å and $n_e=4.5\times10^{11}$ $cm^{-2}$, all the electrons are found in the lowest electron subband $E_1$ at low temperature. To calculate $E_1$ and the band bending $-e\varphi_{sc}(z)$ we have used a self-consistent variational procedure.[13] Similar calculations performed in single GaAs-$Ga_{1-x}Al_xAs$ heterojunctions compare favorably with more elaborate schemes.[14,15] The large barrier height ($V_e=292$ meV) makes the details of the self-consistent potential in the $n$-doped $Ga_{0.61}Al_{0.39}As$ layer to be unimportant in the evaluation of $E_1$. This allows a decoupling between the Poisson and Schrödinger equations on one hand and the equilibrium (electrical and thermodynamical) equations on the other hand.

The nominally undoped GaAs and $Ga_{0.61}Al_{0.39}As$ layers were assumed to contain a residual $p$ doping, with an equivalent areal concentration of $N_{dep}=4.8\times10^{10}$ $cm^{-2}$. We have also investigated the effects of a sheet of negatively charged acceptors (areal concentration $N_A^-$) sitting at the inverted interface. It appears that the energy levels are not strongly influenced by $N_A^-$. However, low values of $N_A^-$ (i.e., less than $10^{10}$ $cm^{-2}$) give a better overall agreement between the measured and calculated transitions. For $L=150$ Å, $n_e=4.5\times10^{11}$ $cm^{-2}$, $N_{dep}=4.8\times10^{10}$ $cm^{-2}$, and $N_A^-=0$, the potential-energy difference across the well is calculated to be 47 meV.

Once $\varphi_{sc}(z)$ was determined, the excited electronic levels $E_i$ ($i\geq2$) were numerically calculated. Because the small GaAs conduction-band nonparabolicity is ignored in our calculations, the in-plane dispersions of the electronic subbands are parabolic and spin degenerate. An average GaAs conduction mass of $0.07m_0$ was used in the calculations.

With the knowledge of $\varphi_{sc}(z)$ and the use of the Luttinger Hamiltonian for the valence band, we have numeri-

cally calculated the in-plane dispersion relations of the valence subbands in the axial approximation following the treatments of Altarelli[16] and Ando.[17] The lack of inversion symmetry of $\varphi_{sc}(z)$ and the large spin-orbit coupling of GaAs and $Ga_{1-x}Al_xAs$ lift the Kramers's degeneracy of the valence levels at finite wave vectors ($\mathbf{k}_\perp$) in the layer plane. The calculated-in-plane dispersions of the valence subbands are presented in Fig. 4. It is worth noticing that the energy difference $HH_1-LH_1$ at the Fermi wave vector is significantly smaller than at zone center. Beside the lifting of the Kramers degeneracy, which magnitude is comparable to that already calculated for single *p*-doped GaAs-$Ga_{1-x}Al_xAs$ heterostructures,[16,17] one notices the strong upward shift of the hole levels due to the tilted aspect of the quantum-well band-edge profile. The holes are preferentially localized near the inverted interface, whereas the electrons are preferentially found near the interface separating GaAs from the doped $Ga_{1-x}Al_xAs$ layer. However, this spatial separation is more effective for lower-lying electron and hole levels and fades away for highly excited subbands ($i>3$).

The gross features seen in the excitation spectra have all been associated with vertical ($k_\perp^{\text{initial}}=k_\perp^{\text{final}}$) intersubband transitions. The transitions ending at $E_1$ were considered to take place at $k_\perp \geq k_F$. The lack of inversion symmetry of $\varphi_{sc}(z)$ lifts the parity selection rule ($\Delta n$ even) which is so prevalent in symmetrical heterostructures.

## IV. INTERPRETATION

The structures observed in the luminescence excitation spectrum have been identified with subband-to-subband optical transitions. The fact that peaks and not steplike structures are observed may arise from enhanced absorptions due to *unbound* excitons[7-9] and/or from resonances in the relaxation mechanisms. It should be kept in mind that luminescence excitation spectra are always the result of an interplay between absorption and relaxation effects. The smoother the absorption onset and the larger are the parts played by relaxation effects.

The subband-to-subband transition energies have been calculated by assuming that the in-plane wave vector of the carrier is conserved during the optical absorption and that the $E_i-LH_j$ and $E_i-HH_j$ peaks correspond to $k_\perp=0$ if $i>1$ and at $k_\perp=k_F$ if $i=1$ where $k_F=(2\pi n_e)^{1/2}$. The lifting of the Kramers's degeneracy of the $n=1$ levels is relatively small in our sample (1.7 and 2.7 meV for $HH_1$ and $LH_1$, respectively) at $k_\perp=k_F$ and we have not found any evidence of such a lifting in our spectra. Thus, the mean energies of the $HH_1$ and $LH_1$ Kramers's doublets have been retained in comparing the experimental and theoretical positions of the $E_1-HH_1$ and $E_1-LH_1$ transitions. With these assumptions, we have been able to reasonably account for the existence and energy spacing of all the observed transitions (but $\delta$). In particular, the energy distance between $HH_1$ and $LH_1$, at $k_\perp=k_F$, is well reproduced by the calculations. This provides evidence indirectly of the positive curvature of the $LH_1$ subband in the vicinity of $k_\perp=0$.

To obtain a good agreement between the absolute positions of the calculated and observed transitions, we have had to use an apparent GaAs band gap. This apparent band gap is 19 meV smaller than the GaAs one. It is most likely due to exchange and correlation effects between the electrons and to correlation effects of the photocreated holes with the electrons.[3-5] Band-gap renormalization effects in symmetrically doped quantum wells have been recently calculated.[3-5] For $n_e=4.5\times10^{11}$ $cm^{-2}$ these calculations indicate that optical transitions are red-shifted by $\sim$20 meV compared with the Hartree calculations.

The photoluminescence line is shifted from the $E_1-HH_1$ peak in the excitation spectrum by 18 meV. This is in good agreement with the calculated 18.9 meV shift between $E_1-HH_1$ at $k_\perp=k_F$ and $k_\perp=0$, respectively. We therefore attribute the photoluminescence line to a recombination between the $E_1$ electron and the $HH_1$ hole at $k_\perp=0$. The shoulder appearing 13 meV above the energy of the luminescence peak when the power of the incident light is increased is likely to be attributed to a $E_1-LH_1$ recombination near $k_\perp=0$ induced by a thermal population of the $LH_1$ subband (the latter is calculated to lie 12.4 meV below the $HH_1$ subband at $k_\perp=0$).

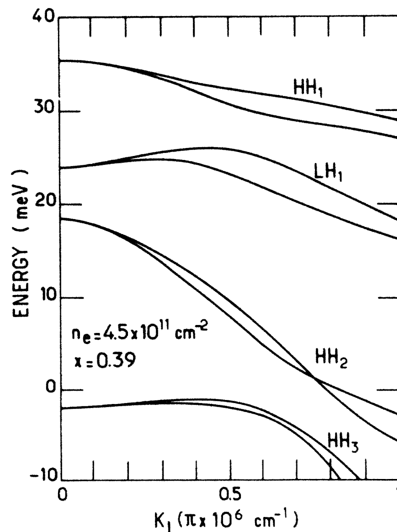


FIG. 4. Calculated in-plane dispersion relations of the valence subbands for the investigated sample. The zero energy is taken at the top of the GaAs valence band at the interface separating GaAs from the doped $Ga_{1-x}Al_xAs$ side (see Fig. 1).

## V. CONCLUSION

We have reported a detailed analysis of optical transitions in doped quantum wells. We have shown that a proper treatment of the electronic self-consistent potential and of the valence-band dispersion relations allows a reasonably good description of the intersubband optical

transitions provided that the GaAs band gap is renormalized. We believe that a careful study of intersubband transitions in modulation-doped quantum wells is a good tool for probing the valence dispersion relations.

Compared with wells doped on either sides the improved mobility of one-side-modulation-doped well favors the choice of these structures for detailed study of energy levels. However, an intriguing feature remains to be elucidated, namely the δ peak whose physical origin has not been determined and might be quite interesting.

## ACKNOWLEDGMENTS

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