Magnetoexcitons in a narrow single GaAs-$Ga_{0.5}Al_{0.5}As$ quantum well grown by molecular-beam epitaxy

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We present a series of magnetoreflectance investigations performed at liquid-helium temperature and up to 55 kG in the Faraday configuration for a narrow single GaAs-$Ga_{0.5}Al_{0.5}As$ quantum well (width around 79 Å). Both right-hand and left-hand circularly polarized magnetoexciton polaritons have been selected for the heavy-hole- and light-hole-related transitions. From the experimental data, taking into account the electron-hole exchange interaction, we could obtain the diamagnetic shifts of both the light-hole and the heavy-hole excitons. We measured an enhancement of the electron Landé factor ($g_c = -6.8\pm0.2$) and a weak influence of the two-dimensional confinement on the valence-band Luttinger parameter ($\kappa = 1.37\pm0.13$).

I. INTRODUCTION

Recently, a great deal of interest has been devoted to the study of magnetoexcitons in the quantum-well (QW) structures GaAs-$Ga_{1-x}Al_xAs$, as a function of the aluminum context x in the barriers and of the well thickness.[1–10] Most of these contributions concentrated to the problem of the exciton binding energy in QW's (Refs. 1, 2, 4, 5, 8, and 9) and to the problem of the diamagnetic shift in such structures.[4,5,10,11] Light- and heavy-hole excitons have different experimental values for the diamagnetic shift and for the effective Rydberg. The above experimental findings agree qualitatively with the predictions of theoretical examinations, but a slight disagreement still remains between the experiments and the numerical calculations. Concerning the problem of g factors, it is worth noting that it has not received intensive consideration up to date;[10] this although some polarized lines had been previously detected at different transition energy.[3,6,10] In this paper, we will present magnetoreflectance investigations performed on a narrow single GaAs-$Ga_{0.5}Al_{0.5}As$ QW at pumped liquid-helium temperature, in the Faraday configuration, the magnetic field being applied parallel to the growth axis of the structure. Then, σ^+ and σ^- transitions can be accurately selected. Our main results are the following: (i) the diamagnetic shifts are smaller than in bulk GaAs and (ii) the quantum-size effect is found to change drastically the electron g factor (g_c) while the corresponding hole one (κ) is less influenced.

II. EXPERIMENTAL CONDITIONS

The magnetic field was produced by a magnetooptic cryostat with a "split pair magnet" and we could reach a maximum value of 5.5 T at 2 K. The source was a tungsten wire lamp. The σ^+ and σ^- reflected beams were selected by a circular setup (formed by a linear Polariod filter and two achromatic Fresnel rhombohedrons) modulated by a 23-Hz chopper and analyzed by a Jobin Yvon HRS monochromator (equipped with a 1200 grooves/mm blazed reflection grating). The optical signal was detected by a photomultiplier followed by a PAR 114 current amplifier and an EG&G 5205 lock-in detector. The QW structure was grown on a Cr-doped (001)-oriented semi-insulating GaAs substrate. The temperature was 600 °C and the As_4:Ga flux ratio was about 4. The growth rate of GaAs was 0.5 monolayers s^{-1}. Growth was interrupted for 2 min at each heterointerface in order to reduce interface-roughness-induced statistical broadening of optical line shapes.[12] A more detailed description of the growth process has been given by some of us in a preceding paper.[13]

III. EXPERIMENTAL RESULTS

Figure 1 displays some of the heavy-hole exciton reflectance patterns obtained for σ^+ and σ^- polarizations, in the case of a 79-Å quantum well width (L_z), when the aluminum content is 0.5 in the barriers. Four exciton-polariton structures can be distinguished in the reflectivity pattern. They originate from one-monolayer steps at the two interfaces of the well which cause a columnar structure of the well.[14] The relative magnitude of the polariton structures reflects the relative distribution of the different well thickness to which they correspond. It is constant whatever the field strength is. This enabled us to follow without ambiguity a given line when the field was changed. In the ranges of field available with our experimental setup (0–5.5 T), transitions could

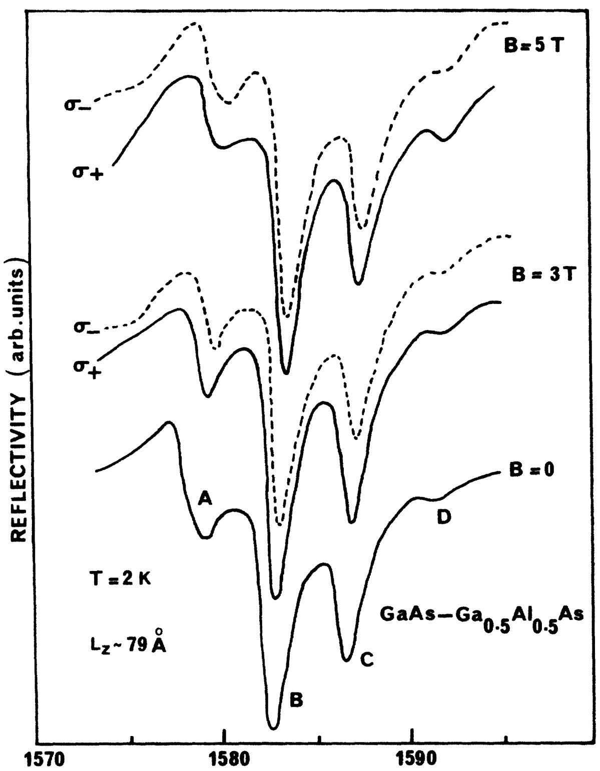

FIG. 1. Reflectivity patterns of the heavy-hole C_1H_1 exciton in a 79-Å-wide GaAs-$Ga_{0.5}Al_{0.5}$As quantum well, for various values of the magnetic field. A,B,C,D represent the four reflectance minima arising from interfacial defects (see text). Clearly, the shape of the structures allows us to follow the changes in the spectrum while changing the magnetic field. Here, both the shift of the transitions and the splitting between the σ^- (dashed lines) and σ^+ (solid lines) recombinations appear to be quite small.

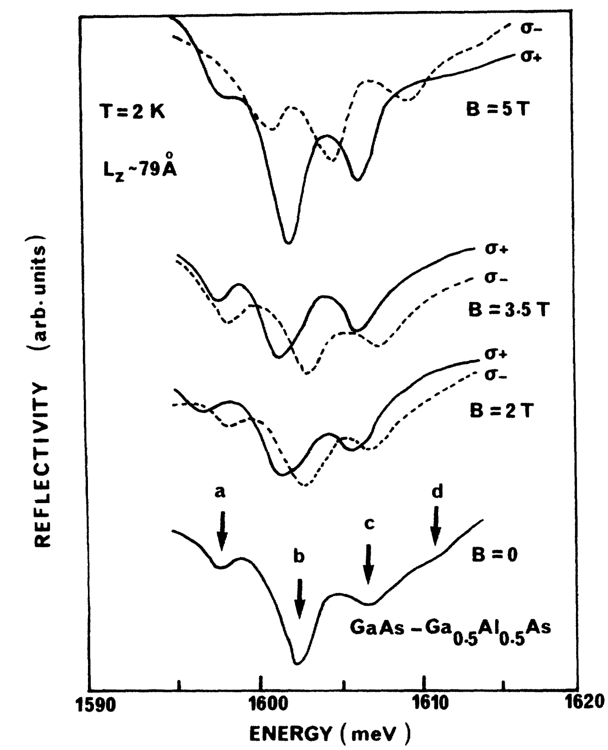

FIG. 2. The same as Fig. 1, but for the light-hole C_1L_1 exciton. Here, the interfacial fluctuations induce four levels—denoted a, b, c, and d—the higher of which is no more observable when the magnetic field increases. The σ^-(dashed line)-σ^+(solid line) splitting is obviously much larger than that of the heavy exciton, the σ^- minima lying always higher in energy than the σ^+ ones.

be observed for σ^+ as well as for σ^- polarizations. The shifts with magnetic field of both σ^+- and σ^--allowed transitions are very similar; the σ^+-σ^- splitting is very weak and can hardly be resolved. Similar observations were reported by Bimberg *et al.* for three-dimensional (3D) GaAs.[15] By direct comparison with these investigations, we can immediately notice the influence of the 2D confinement on the spitting patterns. Figure 2 is the analog of Fig. 1, but now, it depicts the light-hole exciton-polariton. Although we find again four structures at $B=0$, their oscillator strength is smaller and the fourth (the highest in the energy scale) transition (d) can no longer be observed when the field is increased. However, the similarity between the shapes of the light-hole-related and the heavy-hole-related reflectance structures enables us to follow the field shift and field splitting for the three lower-energy light-hole exciton-polaritons. In contrast to the heavy-hole case, we observe well-resolved σ^+-σ^- splittings. The σ^- components lie at higher energy than do the σ^+ ones. Next, comparing with the 3D case we observe a dramatic increase of the splitting due to the quantum-size effect. Similar results, but for the case of GaAs-$Ga_{0.25}Al_{0.75}$As QW's and for much larger well width, have been recently reported by Reynolds *et al.*[10] As illustrated in Fig. 2 of their paper, their reflectivity measurements reveal a larger σ^+-σ^- splitting for light-hole excitons than for heavy-hole ones. In our case although our barriers are shallower ($x=0.5$ in the present case), our well width is smaller and we have encountered the situation where the σ^+-σ^- heavy-hole splitting is not strongly altered by the confinement while the light-hole one is strongly enhanced. Now we will have to deduce the corresponding values of the effective g factors.

IV. DATA ANALYSIS

For our numerical analysis, we have used a simplified version of the Hamiltonian of the exciton in a low magnetic field given by the theory of invariants[15–17] and extensively used with success in the case of GaAs (Refs. 15 and 17) and InP.[18,19] For 3D excitons in GaAs this theory is valid up to 1.5 T.[15] For 2D excitons in GaAs its validity is roughly extended by a factor 4 to ~ 6 T because of the localization-induced increase of the exciton binding energy. The electron-hole exchange interaction has been previously discovered to be large in our sample.[20,21] Limiting ourselves to the four σ-allowed states, in the $|m_h, m_s\rangle$ exciton basis (m_h and m_s are, respectively, the z component of the hole and of the electron angular momentum) one can write the following 4×4 matrix, if the angular dependence of the hole g value and the exchange is neglected ($q=\Delta_2=0$):

$$\begin{array}{cccc} |\frac{3}{2},-\frac{1}{2}\rangle & |\frac{1}{2},\frac{1}{2}\rangle & |-\frac{3}{2},\frac{1}{2}\rangle & |-\frac{1}{2},-\frac{1}{2}\rangle \end{array}$$

$$\begin{bmatrix} E_h+\frac{3\Delta h}{4}-g_c\frac{\mu_B B}{2}-3\tilde{\kappa}\mu_B B & \frac{+\sqrt{3}}{4}\Delta_{hl} & 0 & 0 \\ \frac{+\sqrt{3}}{4}\Delta_{hl} & E_l+\frac{\Delta_l}{4}+g_c\frac{\mu_B B}{2}-\tilde{\kappa}\mu_B B & 0 & 0 \\ 0 & 0 & E_h+\frac{3\Delta h}{4}+g_c\frac{\mu_B B}{2}+3\tilde{\kappa}\mu_B B & \frac{-\sqrt{3}}{4}\Delta_{hl} \\ 0 & 0 & \frac{-\sqrt{3}}{4}\Delta_{hl} & E_l+\frac{\Delta_l}{4}-g_c\frac{\mu_B B}{2}+\tilde{\kappa}\mu_B B \end{bmatrix}$$

where g_c and $\tilde{\kappa}$ are the Landé factors for the electron and hole respectively, μ_B is the Bohr magneton, and B represents the magnitude of the external magnetic field. $\tilde{\kappa}=\kappa-0.28$ for GaAs where κ is the Luttinger parameter of the valence band.[15] Δ_h and Δ_l are the matrix elements of the exchange interaction for heavy-hole and light-hole excitons, and Δ_{hl} is off-diagonal term. Some detailed expressions of these quantities have been reported elsewhere.[21] In contrast to the 3D case, since here we deal with both heavy-hole excitons and light-hole ones, we have to calculate the matrix element of the exchange interaction for two types of exciton envelope functions with different real-space extension. Then, in a spherical approximation the electron-hole exchange being proportional to the probability of finding the electron and the hole inside the same cell can no longer be expressed with a single parameter. In E_h and E_l which can be calculated in the envelope function approximation of Bastard,[22] are competing several contributions such as the change in the effective Rydberg versus magnetic field, diamagnetic shift,[11] superimposed on changes in the confinement energies due to a slight nonparabolicity of the band structure versus magnetic field. The eigenstates of the left-hand 2×2 block-diagonal matrix correspond to σ^+-allowed transitions, the right-hand 2×2 block-diagonal matrix corresponds to σ^-dipole-allowed lines.

Using the calculated values[21] for Δ_h, Δ_l, and Δ_{hl}, one can estimate g_c, κ, and the diamagnetic shifts. After some algebraic manipulations of the analytic solutions of the above matrix one can directly deduce κ and g_c from the experimental value of the transition energies, independently of E_h and E_l. A statistical treatment enabled us to obtain the following set of average values:

$$g_c=-6.8\pm0.2\ ,$$

$$\kappa=1.37\pm0.13\ .$$

Both diamagnetic shifts have been fitted in order to join a good agreement between the experimental data and our theoretical analysis. We have gotten values of 0.0429 $\pm$0.0005 meV T^{-2} and 0.0363$\pm$0.0003 meV T^{-2} for

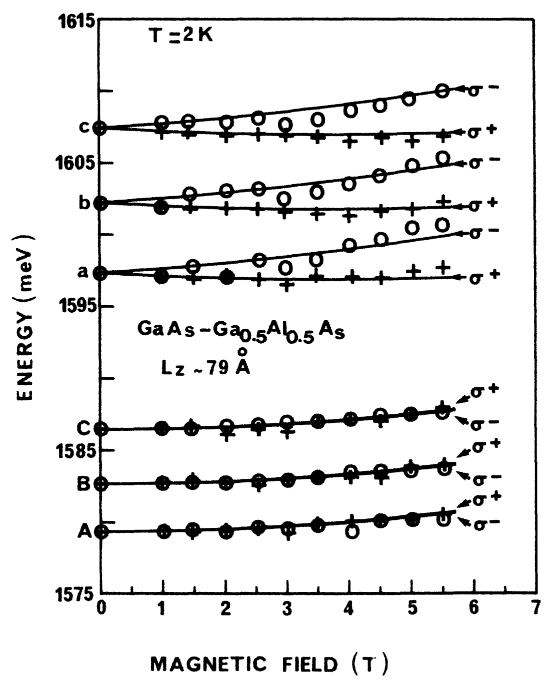

FIG. 3. Plot of the transition energies in the 79-Å-wide $Ga_{0.5}Al_{0.5}As$ QW, vs magnetic field. The experimental points (circles for σ^- and crosses for σ^+ polarizations) have been taken at the minima of the reflectivity structures. The A, B, C, a, b, and c recombinations have been plotted. The solid lines through the experimental points are the result of a numerical fitting, compatible with the following values: $g_c=-6.8\pm0.2$, $\tilde{\kappa}=1.09\pm0.13$, and diamagnetic shifts of $(429\pm5)\times10^{-4}$ meV/T^2 and $(363\pm3)\times10^{-4}$ meV/T^2 for the heavy and light excitons, respectively.

heavy-hole and light-hole excitons, respectively. This trend is in agreement with the predictions of theoretical calculations:[11,23] the diamagnetic shift is larger for heavy-hole excitons than for light-hole ones. The recently reported results of Reynolds *et al.*[10] tend to prove that the experimental trends are smaller than the theoretical treatment predicts. In the case of bulk GaAs the g values of the conduction and valence bands are $g_c = -0.44$ and $\kappa = 1.2$.[15] We have found a smaller influence of the confinement of the hole g factor κ than on the electron one.

The dramatic enhancement of the electron g factor had been previously reported in other types of 2D structures after Shubnikov–de Haas experiments.[24] This result can be understood in the framework of an extension of Roth's[25] theory of g values in semiconductors. The electron g values in three-dimensional GaAs depend in such a delicate manner on details of the band structure that already the sign is difficult to predict with certainty. Slight variations of, e.g., the band gap produce dramatic changes of g_c. In addition, interaction of the lowest conduction band with higher conduction subbands which are close by in energy should be taken into account. For κ, on the other hand, no such strong band-structure dependence is predicted. No evidence of field undulation of g_c already observed in modulation-doped QW's (Ref. 26) has been evidenced in our sample. The comparison between the experiment and the numerical fitting of the minima of reflectance can be made when comparing the solid lines and the experimental points in Fig. 3. We have taken the average values given above for both $\tilde{\kappa}$ and g_c. The slight disagreement between the experimental points and the numerical one can be removed taking into account a weak decrease of $\sim 0.12\%$ per T for g_c and an increase of $\sim 2\%$ per T for $\tilde{\kappa}$. Such changes are believed to arise from nonparabolicity but theoretical investigations should be desirable in order to check that belief.

V. CONCLUSION

We have measured both g_c and $\tilde{\kappa}$ in the case of a high-purity undoped GaAs-$Ga_{0.5}Al_{0.5}As$ QW. The influence of 2D confinement has been found to enhance the electron Landé factor of the electron (which remains negative) and to slightly increase the hole Landé factor.

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