Magneto-optical studies of GaAs-$Al_xGa_{1-x}As$ multi-quantum-well structures grown by molecular-beam epitaxy

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We have measured the diamagnetic shifts of both the heavy-hole and the light-hole excitons as a function of the well size and the magnetic field (up to 36 kG) in GaAs-$Al_xGa_{1-x}As$ multi-quantum-well (MQW) structures using high-resolution optical spectroscopy at liquid-helium temperatures. The applied magnetic field is parallel to the plane of the MQW structures which were grown by molecular-beam epitaxy. We find that in this range of the magnetic field, the diamagnetic shift varies quadratically with the applied field. At a given value of the magnetic field, the diamagnetic shifts of both exciton systems vary almost linearly with the well size. We have also determined, for the first time, the variation of the effective g values of the heavy and light holes as a function of the well size assuming that the electron g value is independent of the well width. A comparison of our measured values of the diamagnetic shifts with those of another group and with the results of a recent calculation is discussed.

INTRODUCTION

The study of the properties of excitons in quantum-well structures has attracted a great deal of interest in the last few years. Recently several groups[1-5] have investigated the behavior of both the heavy-hole and the light-hole excitons in GaAs-$Al_xGa_{1-x}As$ multi-quantum-well (MQW) structures in the presence of a magnetic field. In all these studies the magnetic field is applied perpendicular to the plane of the MQW structures. However, in one of these investigations,[5] the field is also applied parallel to the plane of the structures. From these measurements they determine the variations of the ground-state energies of these excitons (henceforth referred to as diamagnetic shift) as a function of the magnetic field. Several groups[1-4] also observe transitions associated with Landau levels of the free electrons and holes. The simultaneous observation of the magnetic field dependence of the bound and the continuum states allows a direct determination of the band edge and the excitonic ground-state energies and thereby the binding energy in the quantum well. Maan *et al.*[1] have made excitation spectroscopic measurements in several GaAs quantum wells with thicknesses between 50 and 125 Å in high magnetic fields ($B \leq 230$ kG). They observe diamagnetic shifts for heavy- and light-hole excitons. Tarucha *et al.*[2] have studied excitonic transitions in GaAs-AlAs multi-quantum-well structures with different well and barrier thicknesses in the presence of a magnetic field ($B \leq 400$ kG) using absorption spectroscopy. They have determined the diamagnetic shifts of heavy- and light-hole excitons as a function of the magnetic field. A similar study is also reported by Miura *et al.*[3] Ossau *et al.*[4] have measured the diamagnetic shifts of excitons in GaAs-$Al_xGa_{1-x}As$ multi-quantum-well structures in magnetic fields ($B \leq 95$ kG) using photoluminescence spectroscopy. Sakaki *et al.*[5] have determined the diamagnetic shifts of heavy-hole excitons in GaAs-$Al_{0.3}Ga_{0.70}As$ structures with different well sizes using photoluminescence spectroscopy. In their experiments they apply the magnetic field both perpendicular and parallel to the plane of the MQW structure and measure the diamagnetic shifts in both field configurations. In all of these measurements the widths of the excitonic transitions are typically 2–3 meV or more for 100-Å GaAs quantum wells. Recently, Greene and Bajaj[6] have calculated the binding energies of both the heavy-hole and the light-hole excitons in a GaAs quantum well as a function of the well size in the presence of an arbitrary magnetic field applied perpendicular to the plane of the quantum-well structure using a variational approach.

Recently, we have observed[7,8] a sharp-line structure associated with both the heavy-hole and the light-hole excitons in MQW structures composed of GaAs-$Al_{0.25}Ga_{0.75}As$ in photoluminescence (PL) and reflection spectra. Some of the transitions have a linewidth less than or equal to 0.05 meV. In this paper we report the behavior of these transitions in the presence of a magnetic field ($B \leq 36$ kG) applied parallel to the plane of the

MQW structure. In particular, we have measured the diamagnetic shifts of both the heavy-hole and the light-hole excitons as a function of the well size and the magnetic field. We find that in this range of the magnetic field, the diamagnetic shift varies quadratically with the field. For a given value of the magnetic field, the diamagnetic shifts of both exciton systems vary almost linearly with the well size. These measurements are compared with the results of a variational calculation.[9] We have also determined, for the first time, the variation of the effective g values of the heavy and the light holes as a function of the well size using the electron g value appropriate for bulk GaAs. The highly sharp excitonic spectra allow us to determine their behavior in the presence of relatively weak magnetic fields.

GROWTH CONDITIONS

The MQW structures used in this investigation were grown on (100) oriented Si-doped GaAs substrates by molecular-beam epitaxy. The substrates were prepared and loaded in the growth chamber as previously described.[10] The MQW structures were grown at 600 °C. A five-period superlattice consisting of 20-Å $Al_{0.25}Ga_{0.75}As$ and 20-Å GaAs was grown between the substrate and a 0.5-μm-thick GaAs buffer layer on which the MQW structure was then grown. This structure produced MQW's with excellent optical properties.

EXPERIMENTAL TECHNIQUE

The experimental apparatus employed in this investigation permitted high-resolution photoluminescence and reflection measurements to be performed at 2 K and in magnetic fields up to 36 kG. In the intrinsic region of GaAs a dispersion of 0.54 Å/mm was achieved using a 4-m spectrometer. Data were collected on Kodak-type $1-N$ spectrographic plates. The photoluminescence was excited with the 6471-Å line of a krypton-ion laser; for reflection the broad spectrum of a Zr lamp was used.

EXPERIMENTAL RESULTS AND DISCUSSION

The samples used in this study were MQW structures which consisted of $Ga_{0.75}Al_{0.25}As$ barrier layers of thickness 100 Å and GaAs well thickness of 90, 135, 180, 300, and 400 Å. The total number of cycles in the 400- and 300-Å-thick MQW samples was 20, whereas the 180-Å sample had 33 cycles and the 135- and 90-Å MQW's had 50 cycles each. The light-hole free-exciton transitions were observed in PL in only the widest wells, the heavy-hole free-exciton transitions were seen in photoluminescence for all the MQW structures. The reflection spectra were observed for both the light- and the heavy-hole free excitons for all of the MQW's. Typical PL and reflection spectra for the 135-Å MQW are displayed in Fig. 1. Some of the lines are extremely narrow, no more than 0.05 meV full width at half maximum (FWHM). The fine structure is observed over an energy spread corresponding to a well-size fluctuation of about two monolayers. The shift of the fine structure of both the light- and heavy-hole exciton transitions for this MQW for two different applied magnetic fields is shown in Fig. 2. It is noted that all of the fine-structure features for the heavy-hole exciton show the same diamagnetic shift. The light-hole exciton transitions show considerably less diamagnetic shift but do show broadening and splitting with applied magnetic field. This structure is shown in reflection spectra. The reflection spectra for the heavy-hole transitions for the same MQW on an expanded scale are shown for four different applied magnetic fields in Fig. 3. In this figure the individual fine-structure components can be tracked very precisely with applied field. It is clear that all of the components show the same diamagnetic shift. This indicates that the fine-structure transitions are intrinsic in nature and are of similar origin.

The diamagnetic shifts as a function of the magnetic field for bulk GaAs, the 400-Å MQW, and the 180 Å MQW are shown in Fig. 4. The diamagnetic shifts for both the light- and the heavy-hole free excitons are shown for the 400-Å MQW. Only the diamagnetic shift of the

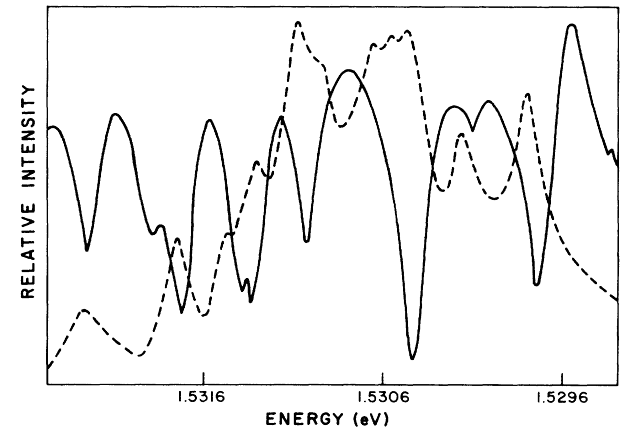

FIG. 1. Optical spectra for a 135-Å MQW sample showing the heavy-hole free excitons. The dashed curve shows the emission spectra; the solid curve shows the reflection spectra.

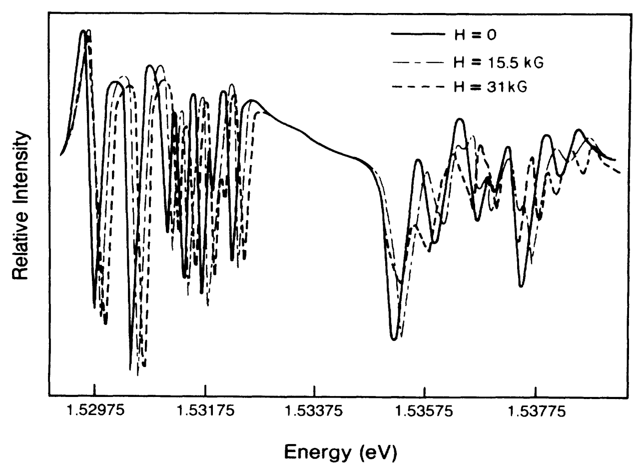

FIG. 2. Shift of the light- and heavy-hole exciton transitions for two different applied magnetic fields. This is a compressed reflection spectra of the MQW sample shown in Fig. 1.

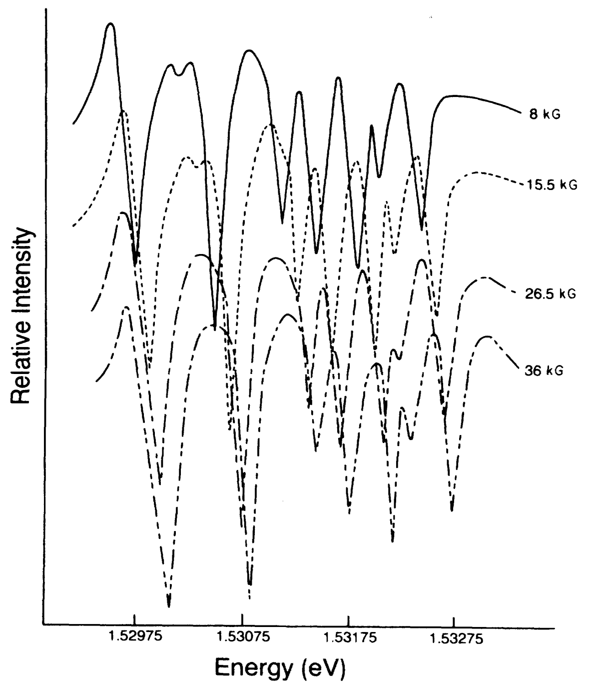

FIG. 3. Shift of the heavy-hole exciton transitions, in an expanded reflection spectra from Fig. 2, for four different applied magnetic fields.

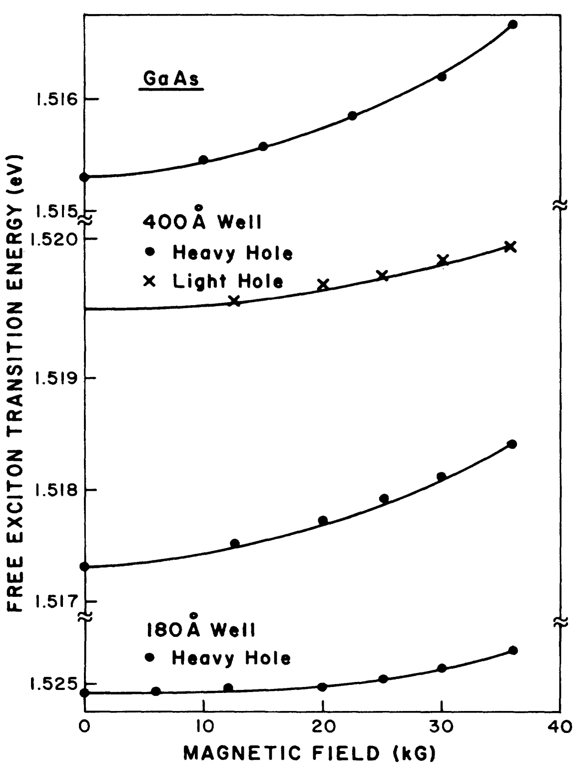

FIG. 4. Diamagnetic shift as a function of H for bulk GaAs. Also shown is the diamagnetic shift for both the light- and heavy-hole free excitons for a 400-Å MQW and the diamagnetic shift for the heavy-hole free excitons for a 180-Å MQW.

heavy-hole exciton for the 180-Å MQW sample is shown. On this scale the diamagnetic shift of the light-hole exciton is barely discernible. Variations of the diamagnetic shifts for both the light- and heavy-hole free excitons as a function of well size for a magnetic field of 36 kG are shown in Fig. 5. A nearly linear relationship is observed with the heavy-hole exciton having a considerably larger diamagnetic shift than the light-hole exciton. Also plotted in Fig. 5 is the variation of the diamagnetic shift of the two exciton systems as a function of the well size as calculated by Greene and Bajaj[9] using Luttinger valence-band parameters proposed by Skolnick *et al.*[11] from their cyclotron resonance studies. Though the theory predicts the correct trends, namely that the diamagnetic shift of the heavy-hole exciton is larger than that of the light-hole exciton and that the diamagnetic shifts of both excitons increase with well size, the theoretical values are considerably larger than the measured ones. For 135-Å MQW structure our measured value of the diamagnetic shift of the heavy-hole excitons at 36 kG agrees with the one determined by Sakaki *et al.*[5] It is not clear why the theoretical values are considerably larger than the experimental values. In their variational calculation of the diamagnetic shift Greene and Bajaj[9] have assumed that the heavy-hole and the light-hole bands are completely decoupled. Recently, Sanders and Chang[12] and Briodo and Sham[13] have calculated the exciton binding energies as a function of the well size using valence-band mixing at zero magnetic field. Both these groups find that for the range of the well sizes used in the present work the binding energies are slightly larger than those calculated as-

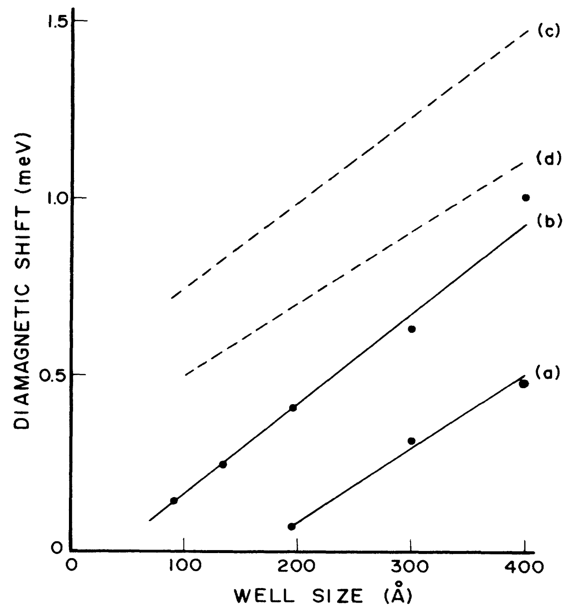

FIG. 5. Variation of the diamagnetic shift of light-hole exciton: line (a), experiment; line (d), theory; and variation of the diamagnetic shift of heavy-hole exciton: line (b), experiment; line (c), theory, as a function of well size at a magnetic field of 36 kG. Solid lines drawn through the experimental points are just aids to the eye.

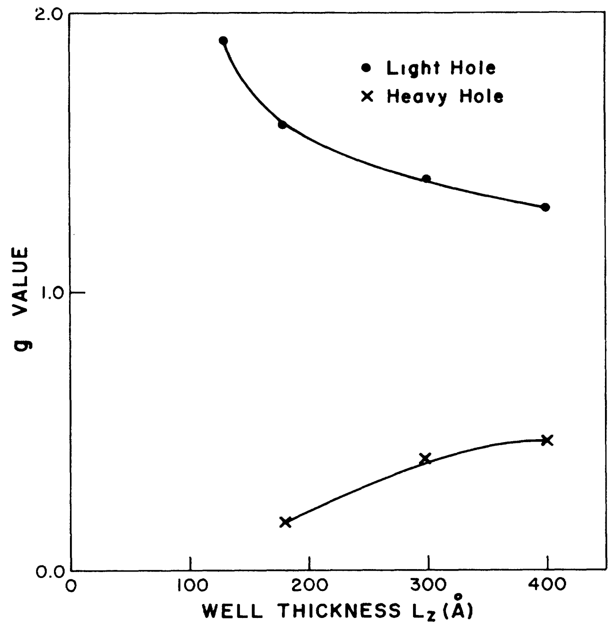

FIG. 6. The light- and heavy-hole g values as a function of well thickness.

suming decoupled bands. It is therefore highly unlikely that the diamagnetic shifts calculated using valence-band mixing will be significantly different from those calculated using decoupled bands. Sakaki *et al.*[5] have also measured the diamagnetic shift of the heavy-hole excitons in GaAs-$Al_{0.3}Ga_{0.7}As$ MQW structures for the case of a magnetic field applied perpendicular to the plane of the structure. They find that for a given value of the well size and magnetic field the value of the diamagnetic shift for the perpendicular field case is about three times larger than that for the parallel field case. Their values of the diamagnetic shifts agree rather well with those calculated by Greene and Bajaj[6] for the perpendicular-field case. For the parallel-field case Greene and Bajaj[9] calculate diamagnetic shifts which are only 20–30% smaller than those calculated for the perpendicular field for the range of well widths considered in the present study.

We have determined the variation of the g values of the heavy and the light holes as a function of well size and display it in Fig. 6. We have assumed that the magnetic field splittings of the free excitons in MQW structures are analogous to those in bulk semiconductors with nondegenerate valence bands (i.e., II-VI semiconductors with wurtzite structure) where the light-hole free exciton splits as the sum of the electron and hole g values and the heavy-hole free exciton splits as their difference. Assuming that the g value of the electron is the same in the quantum wells as in bulk GaAs (0.5), the g values of the holes are determined from the magnetic field splittings. It is noted that the g value of the light hole approaches the GaAs bulk value as the wells get wider. It is not possible for us to compare these results with the predictions of a theoretical model as no such model is available at this time.

CONCLUDING REMARKS

We have measured the diamagnetic shifts of heavy- and light-hole excitons as a function of well size and magnetic field in GaAs-$Al_xGa_{1-x}As$ multi-quantum-well structures using high-resolution optical spectroscopy. The applied magnetic field is parallel to the plane of the MQW structures. Some of the transitions have linewidths as small as 0.05 meV. For the range of magnetic fields (≤ 36 kG) studied, the diamagnetic shift varies quadratically with the field and, for a given value of the field, varies linearly with the well size. We have also determined the variation of the effective g values of the heavy and light holes as a function of the well size. We have compared the values of the diamagnetic shifts we measure with those determined by Sakaki *et al.*[5] and with the results of a variational calculation.[9] We find that our results agree with those of Sakaki *et al.*[5] but are considerably smaller than those predicted by theory.

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