PHYSICAL REVIEW B VOLUME 50, NUMBER 16 15 OCTOBER 1994-II

Magnetoluminescence studies in GaAs-$Al_xGa_{1-x}As$ single heterojunctions: Observation of parity-forbidden Landau-level transitions

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(Received 21 September 1993; revised manuscript received 22 February 1994)

We have observed a number of allowed and parity-forbidden Landau-level transitions in a modulation-doped GaAs-$Al_xGa_{1-x}As$ single heterojunction structure using photoluminescence-excitation spectroscopy at 2 K. The GaAs layer in this structure is 5000 Å thick. From the allowed Landau-level transitions we determine the reduced mass of the electron-hole pair to be $0.07m_e$. Using a heavy-hole mass of $0.45m_e$, we determine the average value of the electron effective mass to be $0.084m_e$. From the parity-forbidden transitions where the hole Landau level is the same but the electron Landau levels are different, we determine the average value of the electron mass to be $0.085m_e$, in excellent agreement with the value determined from the allowed transitions.

I. INTRODUCTION

There has been a great deal of interest in investigating the optical properties of modulation-doped heterostructures during the past few years. This interest has been motivated both by their applications in high-performance electronic devices and fundamental physics. Several groups[1–17] have studied the optical properties of both n- and p-type modulation-doped heterostructures in the presence of a magnetic field and have thus determined the values of the electron and hole masses in both lattice matched and strained systems. In particular, photoluminescence studies in the presence of a magnetic field have yielded a wealth of very useful information. Electrons and holes after reaching thermal equilibrium through nonradiative processes generally recombine via the Landau levels with the same quantum number n $(0,1,\ldots)$, i.e., with $\Delta n=0$, according to a well-known selection rule. The difference in energies between the lowest and the first-excited Landau levels, at a given magnetic field allows the determination of the reduced effective mass of the electron-hole system. Sometime ago, Lyo, Jones, and Klem[3] observed a new class of recombination between the electrons and the holes, namely, off-diagonal transitions (i.e., $\Delta n>0$) in strained modulation-doped quantum-well structures. Similar transitions have also been observed in lattice matched structures.[13,16] These transitions have been attributed to the breakdown of the usual $\Delta n=0$ selection rule due to electron and hole Landau-level mixing caused by the impurity-carrier interactions. The strengths of these transitions have been calculated by Lyo[18] using diagrammatic techniques. Therefore, electron-hole recombination arises not only from the allowed $0\rightarrow0$, $1\rightarrow1$, etc., transitions, but also from the secondary parity-forbidden $1\rightarrow0$, $2\rightarrow0$, $0\rightarrow1$, 0—2, etc., transitions. Here the first number refers to the electron Landau level and the second to the hole Landau level. The observation of the off-diagonal (parity-forbidden) transitions, therefore, allows an independent determination of the electron and hole masses simultaneously in the same sample.

In this paper, we report the observation of both the allowed ($\Delta n=0$) and off-diagonal ($\Delta n\neq0$) transitions in a n-type modulation-doped GaAs-$Al_{0.2}Ga_{0.8}As$ single junction heterostructure at 2 K using photoluminescence excitation (PLE) spectroscopy. We observe a number of transitions of both types in a lattice matched structure in contrast to the above-mentioned references which only report one or two. From the allowed transitions we determine the average reduced mass of the electron-hole system. Using a value of $0.45m_e$ for the heavy-hole mass,[19] we derive the value of the electron effective mass which is consistent with the value determined independently from the off-diagonal transitions.

II. EXPERIMENTAL DETAILS

The sample studied was an $Al_xGa_{1-x}As$-GaAs heterostructure grown by molecular-beam epitaxy on a semi-insulating GaAs substrate. The sample was nominally oriented 2° from (100) towards the nearest (110). A Perkin Elmer cracker cell was used to produce dimeric arsenic as the arsenic growth species. The buffer layer sequence consisted of 500 Å GaAs, followed by a ten-cycle [(30 Å $Al_xGa_{1-x}As$)/30 Å GaAs] superlattice, followed by 5000 Å GaAs with an additional 200 Å Be-doped (10^{15} cm^{-3}) GaAs; this was followed by 20 Å undoped $Al_xGa_{1-x}As$ with an additional 400 Å uniformly doped ($\sim1\times10^{18}$ cm^{-3} Si) $Al_xGa_{1-x}As$. The structure was terminated with a 100 Å GaAs undoped cap. The x value in all cases was 0.2. Hall measurements were carried out at 77 K and analyzed by a technique which

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makes use of the magnetic-field dependence of the conductivity and Hall coefficient in order to separate the two-dimensional electron gas (2DEG) characteristics from those of the heavily doped $Al_xGa_{1-x}As$ and GaAs cap layers.[20] The resulting mobility and carrier concentration were 1.40×10^4 $cm^2/V\,s$ and 1.21×10^{12} cm^{-2}, respectively. This mobility is somewhat lower than what is usually observed with an $Al_{0.3}Ga_{0.7}As$ doping layer (rather than the present $Al_{0.2}Ga_{0.8}As$ layer), and may be at least partially due to higher penetration of the 2D electron wave function into the $Al_{0.2}Ga_{0.8}As$. The knowledge of the 2D carrier concentration allows us to accurately model the band bending.

The PLE spectra were excited with an Ar^+-ion laser-pumped tunable dye laser using Styryl 9 dye. The measurements were made at 2 K with the sample immersed in liquid He. The spectra were analyzed with a high-resolution 4-m spectrometer equipped with an RCAC3134A photomultiplier tube for detection. The magnetic field was applied parallel to the plane of the heterostructure.

III. RESULTS AND DISCUSSION

The photoluminescence (PL) spectra for the heterostructure being studied are shown in Fig. 1. The solid curve shows PL in a zero magnetic field. The sample is being optically excited at 1.5212 eV, slightly above the band gap of GaAs. The transitions that are observed are (1) the acceptor bound exciton Å, X, both the $J=\frac{5}{2}$ and $J=\frac{3}{2}$ states; (2) the donor bound exciton D^0X; (3) the free hole to bound electron, F-B, and (4) the free exciton X. These transitions are all associated with bulk GaAs. The dashed curve shows the PL in an applied magnetic field of 31.4 kG. The same transitions that were observed in zero magnetic field are again present but are shifted to higher energies. An additional transition is also seen, this being labeled X_{2D}. This transition is assumed to be excitonic in character and is associated with the 2DEG and a photoexcited hole. The energy of the X_{2D} transition is consistent with the energy of a similar transition reported by Driessen *et al.*[14]

The PLE spectra, shown in Fig. 2, were obtained by positioning the detector on the X_{2D} transition which has coincidentally the same energy as that of the bulk GaAs free exciton transition. The solid curve shows the spectrum, which is rather featureless, in a zero magnetic field. The dashed curve and the dot-dashed curve show the spectra in applied magnetic fields of 19.0 and 31.4 kG, respectively. Landau oscillations are clearly observed and become more pronounced as the magnetic field increases. Extrapolation of the energies of these oscillations back to zero magnetic field produces the Landau fan diagram shown in Fig. 3. The transitions are labeled as (n_e,n_h), where n_e and n_h designate the electron and hole Landau levels, respectively. In Fig. 4, the allowed and parity-forbidden transitions are shown for a PLE spectra curve taken in an applied magnetic field of 25.8 kG. The horizontal lines are conduction- and valence-band Landau levels. The vertical solid lines designate allowed transitions; the dashed vertical lines are parity-forbidden transitions. It is clear that both allowed $(\Delta n=|n_e-n_h|=0)$ and parity-forbidden $(\Delta n>0)$ Landau-level transitions are observed. The electron and hole energy levels in the presence of a magnetic field B in the parabolic approximation, are given as

$$E(n_e,n_h)=(n_e+\tfrac{1}{2})\frac{\hbar eB}{m_ec}+(n_h+\tfrac{1}{2})\frac{\hbar eB}{m_hc}\ , \tag{1}$$

where m_e and m_h are the appropriate electron and hole masses, respectively. From the allowed transitions, we can, therefore, determine the value of the reduced electron hole mass m^*,

$$\frac{1}{m^*}=\frac{1}{m_e}+\frac{1}{m_h}\ . \tag{2}$$

From parity-forbidden transitions we can determine the values of the electron and hole masses independently. From the four allowed transitions we determine the aver-

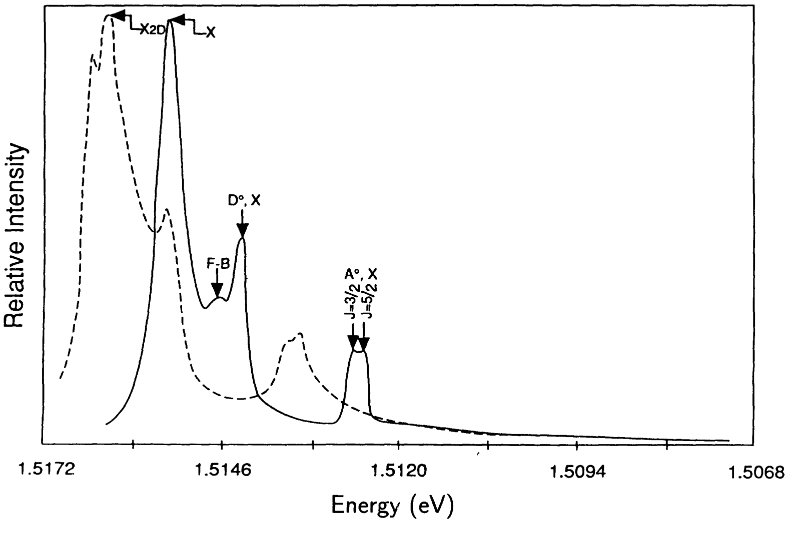

FIG. 1. Photoluminescence spectra for a single $Al_{0.2}Ga_{0.8}As$-GaAs heterostructure. The solid curve is in zero magnetic field; the dashed curve is in an applied field of 31.4 kG.

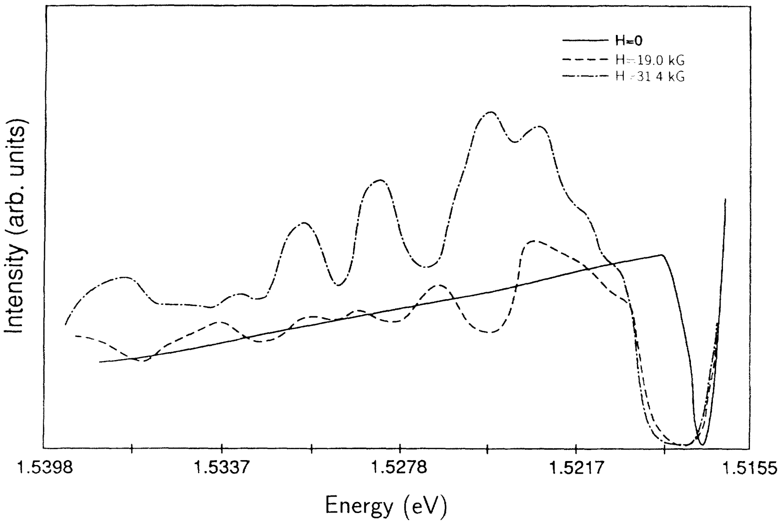

FIG. 2. PLE spectra for the sample shown in Fig. 1. The solid curve is in zero magnetic field; the dashed and dot-dashed curves are in applied magnetic fields of 19.0 and 31.4 kG, respectively.

age reduced mass to be $0.071m_e$. The photoexcited holes are located in the 5000 Å thick GaAs layer and, therefore, experience no confinement effects. To determine the average electron mass from the reduced mass we, therefore, use a value of the heavy-hole mass of $0.45m_e$ which has been determined from cyclotron resonance.[19] We thus obtain $0.084m_e$ as the value of the average electron mass, which is significantly larger than the band edge mass of $0.067m_e$. The mass is larger for at least two reasons. First, the confined electrons experience considerable nonparabolicity effects which enhance the value of the effective mass. Second, there is a significant penetration of the electronic wave function into the $Al_{0.2}Ga_{0.8}As$ barrier thus leading to a large value of the effective mass. Enhanced values of the effective mass of confined electrons have been reported by several groups.[12,16,17,20,21] As pointed out earlier, we can also determine the value of the electron effective mass independently from the nonallowed (off-diagonal) transitions such as (1-0), (2-0), (3-0), etc.; the average value of the electron mass obtained from

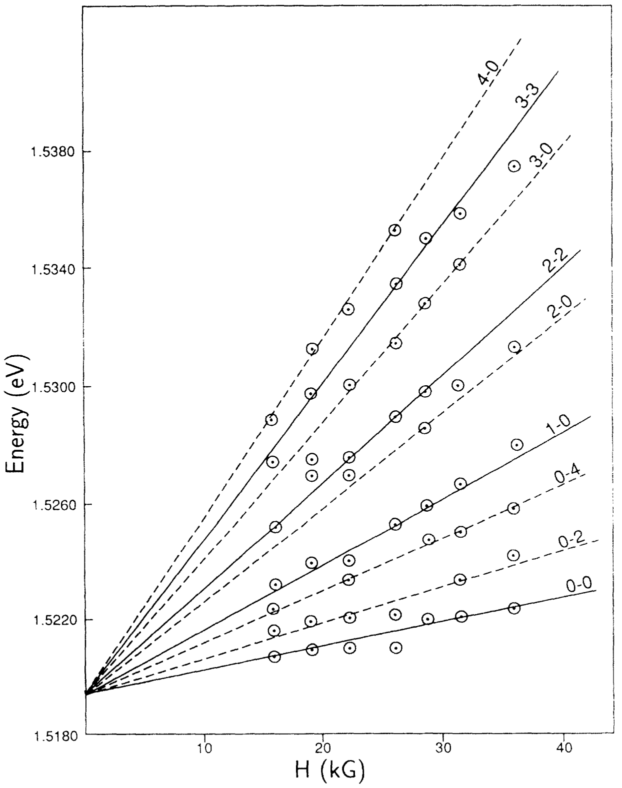

FIG. 3. Landau fan diagram. The solid lines are allowed transitions; the dashed lines are parity forbidden transitions.

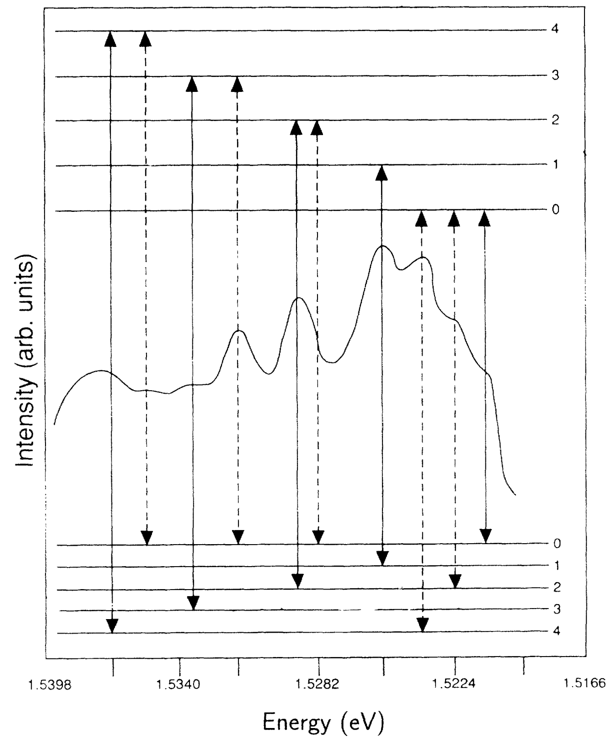

FIG. 4. The allowed (solid lines) and unallowed (dashed lines) for a PLE spectra curve taken at 25.8 kG. The horizontal lines are conduction and valence-band Landau levels.

these transitions is $0.085m_e$ which agrees very well with that determined from the allowed transitions.

The identification of the off-diagonal transitions in which the electron Landau levels are the same but the hole Landau levels are different is somewhat tentative. In Fig. 3, we display two transitions which we designate as (0-2) and (0-4), since this assignment is consistent with the hole mass of $0.45m_e$. It is not clear to us why we do not observe other transitions such as (0-1) and (0-3).

As mentioned earlier, the main purpose of this work is to report the observation of a number of allowed and parity-forbidden Landau-level transitions in a modulation-doped GaAs-Al$_{0.2}$Ga$_{0.8}$As single heterojunction structure using photoluminescence excitation spectroscopy and explain their energy positions using a consistent set of electron and hole mass parameters and not to claim to determine their very accurate values. For that purpose one should use cyclotron resonance technique. We do find that the value of the electron effective mass determined from the allowed transitions generally increases with the quantum numbers of the Landau levels consistent with the effects of the enhanced nonparabolicity and larger penetration of the electronic wave function into the barrier. The electron effective mass determined from the parity-forbidden Landau-level transitions also shows a similar general behavior. We have, however, not emphasized this point due to uncertainties in some of the data points displayed in Fig. 3 and, therefore, have used the concept of the average electron effective mass to explain the overall features of the observed spectra.

In order to obtain the electron effective mass from the allowed Landau-level transitions we have used a value of $0.45m_e$ for the heavy-hole mass. This mass was determined by Skolnick *et al.*[19] using cyclotron resonance at liquid-nitrogen temperature, i.e., under almost classical conditions. Our measurements are made at 2 K and do not exhibit any quantum effects attributable to the valence-band structure. Similar observations have also been reported by other groups.[4,16,17] The reason for this behavior is not clear at this moment.

IV. CONCLUSIONS

We have observed a number of allowed and parity-forbidden Landau-level transitions in a modulation-doped GaAs-Al$_{0.2}$Ga$_{0.8}$As single heterojunction structure using photoluminescence-excitation spectroscopy. From the allowed Landau-level transitions we determine the reduced mass of the electron hole pair to be $0.07m_e$. Using a heavy-hole mass of $0.45m_e$ we determine the average value of the electron effective mass to be $0.084m_e$. From the parity-forbidden transitions where the hole Landau level is the same but the electron Landau levels are different, we determine the average value of the electron mass to be $0.085m_e$, in excellent agreement with the value determined from the allowed transitions.

ACKNOWLEDGMENTS

The authors would like to thank J. E. Ehret and E. N. Taylor for crystal growth support and G. L. McCoy and C. W. Litton for technical support. This work was partially supported by AFOSR. The work of D.C.R., D.C.L., and B.J. was performed at Wright Laboratory, Solid State Electronics Directorate (WL/EL), Wright Patterson Air Force Base under U.S.A.F. Contract No. F33615-91-C-1765. The work of KKB was supported by Grant No. AFOSR-91-0056.

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