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Magnetotransport properties and subband structure of the two-dimensional hole gas in GaAs-$Ga_{1-x}Al_xAs$ heterostructures

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Systematic magnetotransport measurements of two-dimensional holes in various GaAs-$Ga_{1-x}Al_xAs$ heterostructures are reported. The behavior of a heterojunction and a 200-Å quantum well can be explained on the basis of zero-field spin-split subbands, whereas that of a 100-Å quantum well is consistent with a spin-degenerate ground subband in the absence of a magnetic field. However, in a 50-Å quantum well we found an unusual relation between the filling factor and the spin splitting.

The two-dimensional electron gas (2DEG) in GaAs-$Ga_{1-x}Al_xAs$ heterostructures has proved to be an excellent system for the experimental study of such interesting physics as the integral and fractional quantum Hall effects (QHE).[1] Growing effort[2-4] has been recently directed toward the study of the two-dimensional hole gas (2DHG) with interest in the QHE in hole systems and in a wide variety of new phenomena arising from the complexity of the valence-subband structure, to mention only a few.

The subbands of a *p*-channel heterostructure basically consist of two series of levels originating from the heavy-hole and the light-hole bulk valence bands. In a typical range of two-dimensional hole concentrations ($n < 1\times10^{12}$ cm^{-2}), only the lowest heavy-hole subband is populated. In the case of a heterojunction, the lack of inversion symmetry combined with the strong spin-orbit coupling lifts the spin degeneracy at finite values of the wave vector even in the absence of magnetic field.[5,6] Experimental support for this has been provided by a cyclotron resonance experiment[2] in which two resonance peaks corresponding to effective masses of 0.38 and 0.60 (in the unit of the free electron mass) have been observed for a sample with hole density $n=5\times10^{11}$ cm^{-2}. A study of the Shubnikov–de Haas (SdH) spectrum has also found a consistent interpretation along this line.[3] In the case of a quantum well, it is expected that the inversion symmetry restores the spin degeneracy. The experimental answer to this problem, however, seems ambiguous. While a SdH experiment[3] for a 100-Å well suggests no spin splitting at zero magnetic field, a light-scattering experiment[7] on a similar well reveals a low-energy excitation peak which is attributed to a transition between spin-split ground subbands.

In the present study, we have prepared a series of *p*-channel heterostructures with different symmetries, including a heterojunction, an asymmetric quantum well, and symmetric quantum wells of various well thicknesses. We discuss the magnetotransport properties of these heterostructures in the light of recent theoretical calculations of the valence-subband structure.[8-11] Samples used in the present study were grown by molecular-beam epitaxy on semi-insulating (100) GaAs substrates. $Ga_{1-x}Al_xAs$ was selectively doped with Be to make *p*-channel heterostructures. Details of the sample preparation are found in Ref. 12. The samples were etched into a Hall bar shape and Ohmic contacts were made by diffusive alloying of indium-cadmium. Table I summarizes the characteristics of the samples. Sample A is a heterojunction. Samples B, C, and D are single quantum wells with well thickness of 200, 100, and 50 Å, respectively. Sample E is a 50-Å, single quantum well fabricated asymmetric by doping only on one side of

TABLE I. Carrier density, determined from either the quantum Hall effect (n_{QHE}) or Shubnikov–de Haas oscillations (n_{SdH}), effective mass m^*, relaxation time τ_{SdH}, and scattering time τ_{mob} of the various samples studied.

Sample	n_{QHE} (10^{11} cm^{-2})	n_{SdH} (10^{11} cm^{-2})	m^*	τ_{SdH} (psec)	τ_{mob} (psec)
A. heterojunction ($x=0.43$, $d_s=240$ Å)	3.80	1.22	0.13–0.18	1.7	6.5
B. 200-Å quantum well ($x=0.37$, $d_s=350$ Å)	4.69	1.43	···	···	···
C. 100-Å quantum well ($x=0.37$, $d_s=250$ Å)	6.78	3.38×2	0.43–0.56	0.4	16.7
D. 50-Å quantum well ($x=0.37$, $d_s=250$ Å)	6.82	3.40×2	0.16–0.23	0.7	2.7
E. 50-Å asymmetric quantum well ($x=0.37$, $d_s=235$ Å)	2.57	$1.24+1.31$	0.2–0.3	···	6.8

the well. The Al content x in the GaAlAs layer and the thickness of the undoped GaAlAs spacer layer are given in Table I.

Figure 1 shows the magnetoresistance ρ_{xx} and the Hall resistance ρ_{xy} of the heterojunction (sample A). At sufficiently high magnetic fields, where magnetic levels are well separated from each other, the periodicity in $1/B$ of the structures in ρ_{xx} carries only the information of the total carrier density. The total carrier density derived in this QHE regime for this sample is $n_{\mathrm{QHE}}=3.8\times10^{11}$ cm^{-2}. In the low-field range, the SdH spectrum yields useful information on the subband structure. The carrier density derived from the period of the low-field SdH oscillations is $n_{\mathrm{SdH}}=1.2\times10^{11}$ cm^{-2}, much lower than n_{QHE}. As pointed out earlier,[2,3] this means that the heavy hole ground subband is spin split at zero field, and only the lighter mass carrier is observed in the low-field SdH oscillations. The effective mass deduced from the temperature dependence of the SdH amplitude is $m_1\approx0.13$–0.18 for the field range of $4<B<8$ kG, where the analysis is done. This value is significantly lower than other reported values, i.e., $m_1\approx0.36$ (Ref. 2) and $m_2\approx0.24$ (Ref. 3) for samples with $n\approx5\times10^{11}$ cm^{-2}.

A recent calculation by Ando[10] of the valence-subband structure shows that the mass for the spin-down branch of the ground heavy-hole subband is $m_1\approx0.18$ and is only weakly dependent on the hole density, whereas the spin-up branch is highly nonparabolic and the mass changes from $m_2\approx0.3$ at $n\approx1\times10^{11}$ cm^{-2} to ≈0.9 at $n\approx4\times10^{11}$ cm^{-2}, above which the dependence becomes weak. Other theoretical calculations give $m_1\approx0.17$ and $m_2\approx0.44$ (Ref. 8), $m_1\approx0.12$ and $m_2\approx0.46$ (Ref. 9), and $m_1\approx0.15$ and $m_2\approx0.61$ (Ref. 11), all for $n\approx5\times10^{11}$ cm^{-2}. The theoretical values for the lighter mass are close to each other and to our experimental value. An estimate of the heavier mass from the lighter mass and the population ratio yields $m_2\approx0.28$–0.39 for our sample, which is smaller than the other reported values, $m_2\approx0.60$ (Ref. 2) and ≈0.59 (Ref. 3). Part of the difference may be attributed to the nonparabolicity of the spin-up branch, since our sample has $\approx24\%$ less carriers than those in Refs. 2 and 3. However, one should also remember that this method of estimate, based on the population ratio, is not very reliable in the presence of strong nonparabolicity and tends to give a lower value than the actual mass at the Fermi level. The field range of the cyclotron resonance experiment is generally higher than that for the low-field SdH measurements, and the field dependence of the mass is expected to be significant.[10] The theoretical value for the heavier mass seems to be sensitive to the method of calculation, and a clear comparison between theory and experiment is difficult at the present stage.

The behavior of the 200-Å single quantum well (sample B) is similar to the heterojunction. The hole densities deduced from the QHE and from the SdH period are $n_{\mathrm{QHE}}=4.69\times10^{11}$ cm^{-2}, and $n_{\mathrm{SdH}}=1.43\times10^{11}$ cm^{-2}, respectively. It is reasonable, therefore, to conclude that in the 200-Å well the ground level is in the cusp part of the self-consistent potential, and that the symmetry situation is similar to the heterojunction case.

Figures 2 and 3 are the traces of ρ_{xx} and ρ_{xy} for the 100-Å single quantum well (sample C) and the 50-Å single quantum well (sample D), respectively. The total hole density is roughly the same for these samples, $\approx6.8\times10^{11}$ cm^{-2}. The hole density calculated from the SdH period agrees with n_{QHE} if twofold spin degeneracy is taken into account. The spin splitting is resolved at fields higher than ≈40 kG. The abrupt appearance of the spin splitting is probably attributed to the exchange enhancement mechanism as discussed for the Si metal-oxide semiconductor system[13] and n-channel heterostructure.[14] The effective mass we obtain for the 100-Å quantum well ranges from 0.43 to 0.55 in the field range $12<B<25$ kG, while that for the 50-Å quantum well is 0.16 to 0.23 in the field range $9<B<22$ kG. A theoretical calculation[10] for a multiple quantum well with ≈100-Å(GaAs)/150-Å(GaAlAs) period gives a highly nonparabolic mass ranging from 0.27 for $n=2\times10^{11}$ cm^{-2} to 0.99 for $n=5.8\times10^{11}$ cm^{-2}. Our ex-

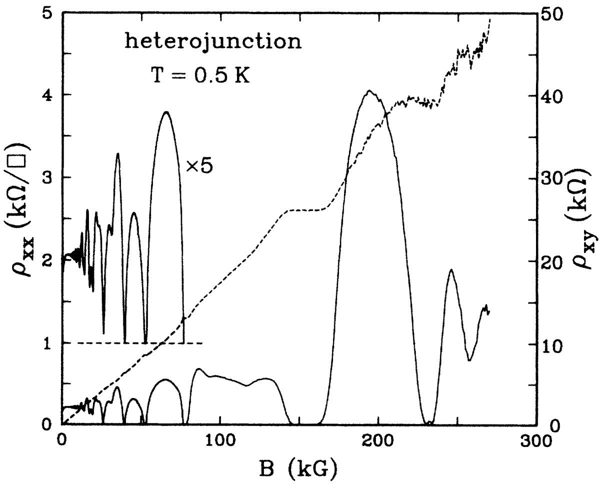

FIG. 1. Experimental traces of ρ_{xx} and ρ_{xy} for the heterojunction (sample A). The low-field part is shown in a scale expanded five times. At the highest fields, minima in ρ_{xx} associated with the filling factors $\nu=\frac{2}{3}$ and $\frac{3}{5}$ are seen.

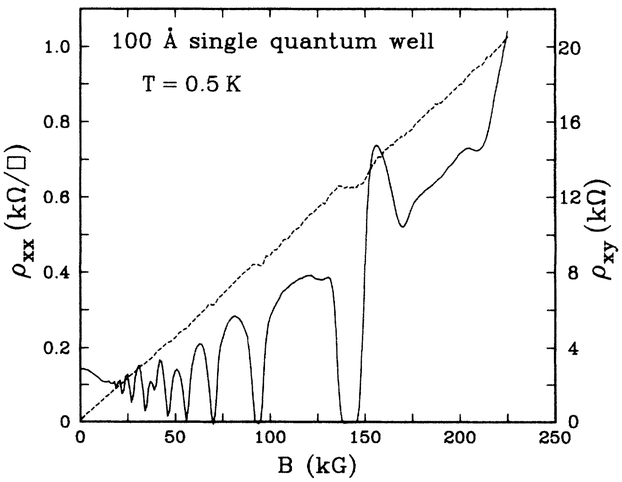

FIG. 2. Traces of ρ_{xx} and ρ_{xy} for the 100-Å single quantum well (sample C). The Zeeman spin splitting is resolved at fields higher than ≈35 kG. The shallow dips around 170 and 210 kG correspond to $\nu=\frac{5}{3}$ and $\frac{4}{3}$.

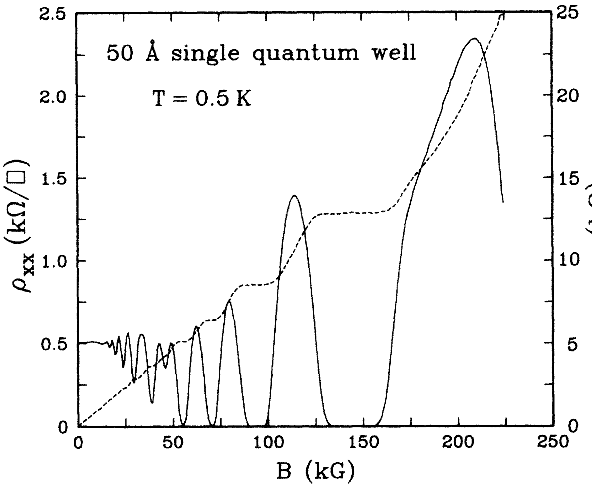

FIG. 3. Traces of ρ_{xx} and ρ_{xy} for the 50-Å single quantum well (sample D). Notice the unusual relation between the filling factor (identifiable from the ρ_{xy} value) and the "spin-split" pair around 47 kG.

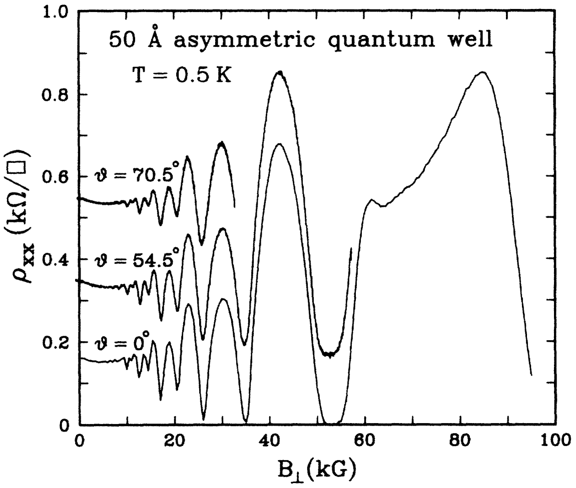

FIG. 4. Traces of ρ_{xx} for the 50-Å asymmetric quantum well (sample E) at different tilt angles of the magnetic field from the perpendicular direction. The horizontal scale is the perpendicular component of the field.

perimental value of $m \approx 0.5$ for the 100-Å quantum well is small compared with the theoretical value for the corresponding hole density, but is in good agreement with recent cyclotron resonance measurements.[15] The calculation[10] has been made using the 85%–15% rule. The agreement with the experiment will be improved if a larger valence-band offset is assumed. The effective mass for the 50-Å quantum well is considerably smaller than that for the 100-Å well. This is qualitatively explained by considering that the wider the quantum well, the closer the light-hole level to the heavy-hole ground level, and hence, the larger the nonparabolicity of the ground subband. A quantitative comparison, however, is rather difficult because of the number of parameters involved in the theoretical calculation. We note an unusual relation at high fields between the "spin splitting" and the filling factor for the 50-Å quantum well. Namely, as can be identified by the corresponding value of the quantized Hall resistance, the filling factor at the middle dip of the "spin-split" pair around $B = 47$ kG is $\nu = 6$, while this should be an odd integer for an ordinary sequence of magnetic levels. The relation is normal for the 100-Å quantum well. We shall discuss these points later in this paper.

Figure 4 shows the trace of ρ_{xx} for the 50-Å asymmetric quantum well. The SdH spectrum is composed of two series of peaks. The periods of the two series yield hole density of 1.24×10^{11} cm^{-2} and 1.31×10^{11} cm^{-2}, whose sum agrees with the total hole density $n_{\mathrm{QHE}} = 2.57 \times 10^{11}$ cm^{-2}. In other words, the spin splitting is well resolved at fields as low as ≈ 10 kG. Traces of ρ_{xx} taken under tilted magnetic fields are also shown in Fig. 4. It is seen that the traces coincide with one another when the horizontal axis is scaled by the perpendicular component of the magnetic field. These facts suggest that the subband is already spin split at zero field, and two separate Landau ladders are generated from the two branches, although the zero-field spin splitting is much smaller than in the heterojunction case. The effective-mass determination for this sample suffers from the nonsinusoidal waveform of the SdH oscillations and is not very accurate. Nevertheless, the value of the mass we obtain falls in the range of 0.2–0.3, and is again considerably smaller than that for the 100-Å well.

We summarize the above-described experimental results as follows.

(a) The magnetotransport behavior in the heterojunction is understood on the basis of the zero-field spin-split subband structure. The lighter effective mass is in good agreement with theoretical estimates.[8–11] The heavier mass shows more disagreement among theories and experiments.

(b) The 200-Å quantum well is basically similar to the heterojunction, as the ground level lies in the cusp part of the potential.

(c) The behavior of the 100- and the 50-Å quantum wells is consistent with a spin-degenerate ground subband in the absence of magnetic field.

(d) The effective mass is ≈ 0.5 for the 100-Å quantum well and ≈ 0.2 for the 50-Å quantum well. The qualitative trend is explained in terms of the degree of mixing of the light-hole subband.

(e) The ground subband of the 50-Å asymmetric quantum well is spin split at zero magnetic field, but the splitting is not so large as the heterojunction case, and the holes in both subbands are visible in the low-field SdH oscillations.

The unusual relation between the filling factor and the "spin splitting" observed in the 50-Å quantum well is difficult to understand in terms of an ordinary Landau-level scheme with spin splitting. Since this behavior is observable even at high magnetic fields, in the QHE regime, it should be independent of the complexities of the subband structure. A possible explanation, by assuming such a g factor that adjacent Landau levels with opposite spins coincide, is ruled out by an experiment under tilted magnetic fields. Namely, while such an accidental degeneracy should be easily lifted by a tilted field, traces of ρ_{xx} under tilted fields show no such splitting. The unusual relation, therefore, suggests that the labeling of the magnetoresistance oscillations as spin-split Landau levels may not be correct, and that splitting may exist even at zero magnetic field, in contradiction with the simple model of Ref. 4.

Finally, we mention briefly the carrier relaxation time. The last two columns of Table I give the scattering time estimated from the magnetic field dependence of the SdH amplitude and that from the zero-field mobility, using the effective-mass values listed. Large discrepancies are seen between the two quantities. A similar discrepancy is reported for the case of an electron gas,[16] and is attributed to inhomogeneous broadening of Landau levels due to long-range potential fluctuations. The ratio between the two scattering times ranges from 4 to 40 among our samples and is particularly large for the 100-Å well. This may provide a way to characterize the nature of disorder in different heterostructures, although more data have to be accumulated to find a systematic trend.

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