Energy Structure and Quantized Hall Effect of Two-Dimensional Holes

H. L. Stormer and Z. Schlesinger
Bell Laboratories, Murray Hill, New Jersey 07974

and

A. Chang and D. C. Tsui
Department of Electrical Engineering and Computer Science, Princeton University, Princeton, New Jersey 08540

and

A. C. Gossard and W. Wiegmann
Bell Laboratories, Murray Hill, New Jersey 07974

(Received 18 February 1983)

Combined magnetotransport and cyclotron-resonance experiments in a two-dimensional hole system at a modulation-doped GaAs-(AlGa)As heterojunction show that the Kramers degeneracy of the lowest subband is lifted for finite k giving rise to two cyclotron masses $m_1^* = 0.38m_0$ and $m_2^* = 0.60m_0$ at $E_F = 2.4$ meV. The observation of plateaus in ρ_{xy} shows that the quantized Hall effect is independent of the details of the host band structure.

PACS numbers: 73.40.Lq, 71.45.-d, 72.20.My, 73.60.Fw

While the properties of two-dimensional (2D) electron systems have received much attention in recent years, little interest has been shown in 2D hole systems.[1] This is largely due to the fact that hole masses are heavier than electron masses and as a result they have lower carrier mobilities and smaller Landau-level splittings. In particular, magnetotransport and cyclotron-resonance measurements suffered from a small $\omega_c\tau\ (=B\mu)$ which made only the coarsest features of the 2D-hole subband level scheme accessible to experiment. This is unfortunate, since 2D hole systems, because of the intricacy of the valence-band structure of their host material (containing degeneracies and strong anisotropies), are expected to show rich spectra in experiments of this kind. In fact, in spite of the complexity of 2D-hole subband levels, some general features common to all 2D hole systems can be deduced from simple symmetry considerations. The lifting of the Kramers degeneracy of each subband level, which is induced by the absence of inversion symmetry of the roughly triangular, carrier-confining potential well, is one of the most outstanding features.[2,3] So far there has been no experimental proof for the existence of such an effect.

With the advent of modulation doping[4] it is now possible to manufacture 2D hole systems with exceedingly high mobilities[5] and to investigate their transport properties in detail. In this paper we report on combined Shubnikov–de Haas and cyclotron-resonance experiments on a 2D hole system at a modulation-doped GaAs-(AlGa)As heterojunction interface. Our results show that the Kramers degeneracy of the lowest two hole subbands is lifted for finite k giving rise to two cyclotron masses. At $k=0$ both subbands remain degenerate. The simultaneous observation of the quantized Hall effect (QHE)[6,7] in this 2D hole system plays an important role in our determination of the subband structure. Moreover, its observation demonstrates that this novel quantum phenomena is not limited to 2D electron systems and is indeed independent of the intricate details of the host band structure.

The sample was prepared by molecular-beam epitaxy and consisted of a Cr-doped (100) GaAs substrate, overgrown with 1 μm of undoped GaAs followed by 70 Å of undoped (AlGa)As and covered by 500 Å of (AlGa)As doped with Be to ~ 1×10^{18} cm^{-3}. The Al mole fraction was 50%. Because of the transfer of holes from acceptors in the (AlGa)As to the valence-band-edge states of GaAs, a 2D hole gas is established at the GaAs-(AlGa)As interface.[5] For transport measurements a specimen was cut in the shape of a Hall bar and contacted by standard Au:Zn diffusion. The magnetotransport measurements were performed at temperatures between 4.2 and 0.55 K in magnetic fields up to 210 kG perpendicular to the plane.

Figure 1 shows the results for ρ_{xx} (Shubnikov–de Haas effect) and ρ_{xy} (Hall effect) of the 2D holes as a function of magnetic field at a temperature of 0.55 K. Two distinct sets of oscillations are observable in ρ_{xx}, one of which ceases at ~35 kG, where the other set begins to appear. In the vicinity of 100 and 200 kG, ρ_{xx} approaches the zero-resistance state. At these same field positions, ρ_{xy} develops plateaus characteristic of the QHE. All features are very clearly developed and resemble the data on 2D electron systems, reflecting the high quality of the 2D hole gas. Accurate measurements on ρ_{xx} and ρ_{xy} were performed on the last plateau ($i=1$). ρ_{xy} was compared to a standard resistor[8] while ρ_{xx} was measured directly with a high-resolution digital voltmeter. We found ρ_{xy} to be quantized to $\rho_{xy}=h/e^2$ to better than one part in 10^4, which was the limit of the accuracy of our standard resistor. At the same field $\rho_{xx} \leq 1\ \Omega$. Although the accuracy of the quantized resistance can be improved by using a more precisely calibrated resistance standard,[9] the present result already shows that the QHE is not limited to 2D electron systems but also occurs in 2D hole systems. It demonstrates that this quantum phenomenon is universal and not limited by any peculiarities of the band structure of the host material.

Two features of the data are direct consequences of the subband structure of the holes. One is the occurrence of two sets of quantum oscillations, suggesting the population of two subbands. The other is the relative width of the plateaus in $\rho_{xy}=h/ie^2$ for $i=1$, 2, and 3. In the case of electron systems, plateaus with even indices occur at higher temperatures and develop into wider structures than those having odd indices.[6,7] This effect is attributed to a spin splitting of each Landau level into two singularities. Since the Landau splitting greatly exceeds the spin splitting, plateaus related to the lifting of the spin degeneracy develop at relatively lower temperature. The Hall plateaus observed in the hole system, as seen in Fig. 1, do not show this odd/even discrepancy. In fact the width and the T development of the $i=3$ plateau are similar to those of the $i=2$ and 4 plateaus. This unique feature results from the lifting of the spin degeneracy of the 2D holes at the heterojunction interface. These observations together with our cyclotron-resonance measurements allow us a direct determination of the subband structure of the holes.

The QHE plays an important role in our band-structure determination. The observation of $\rho_{xy}=h/e^2$ at $B=206$ kG allows us to conclude unambiguously, without the knowledge of any details of the subband structure, that only one singularity is occupied and hence that the density is $n=eB/hc=(5.0\pm0.05)\times10^{11}$ cm^{-2}. The standard plot of the inverse of field positions of the maxima and the minima in ρ_{xx} versus their index is shown in Fig. 2. Two straight sections belonging to the two sets of oscillations are evident. Their slopes are $s_1=80.6$ kG and $s_2=206$ kG, respectively. The results of far-infrared cyclotron-resonance experiments on the same sample in fields up to 80 kG are shown in Fig. 3. They reveal the existence of two carriers with two different masses: $m_1^*=0.38m_0$ and $m_2^*=0.60m_0$. Since the heavy- and light-hole cyclotron masses in bulk GaAs in the (100) direction are $m_h^*=0.49m_0$ and $m_l^*=0.086m_0$,[10,11] respectively, the observed cyclotron masses of the 2D holes suggest that both are derived from the heavy-mass hole band of bulk GaAs. From the temperature dependence of the amplitude of the low-field oscillation (not shown) we deduce a mass of $m^*=(0.36\pm0.03)m_0$, clearly relating this oscillation to the smaller one of the two observed cyclotron masses, i.e., m_1^*.

From these data we conclude that there exist two hole subbands with densities n_1 and n_2, masses m_1 and m_2, and Fermi energies E_{F1} and E_{F2}.

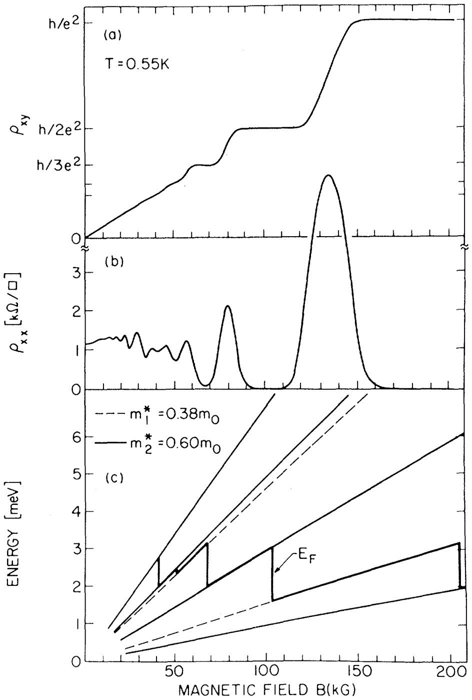

FIG. 1. (a) Off-diagonal (ρ_{xy}, Hall effect) and (b) diagonal (ρ_{xx}, Shubnikov–de Haas) resistivity of a two-dimensional hole gas at a modulation-doped GaAs-(AlGa)As heterostructure as a function of magnetic field at $T=0.55$ K. (c) Landau fan and Fermi-level position using the masses determined by cyclotron resonance (see Fig. 3 and text).

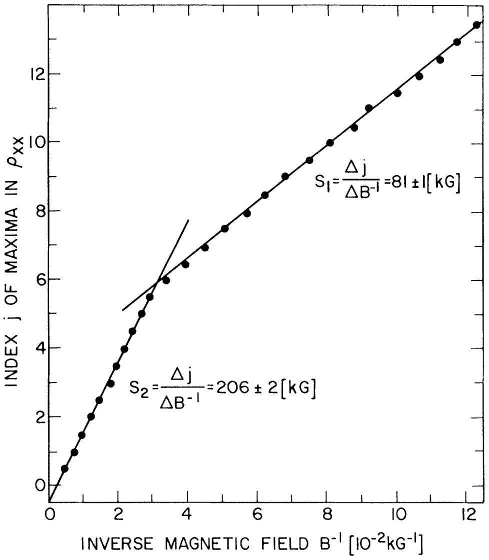

FIG. 2. Plot of the inverse field position of the maxima and the minima in ρ_{xx} vs their index. s_1 and s_2 are the slopes of the low-field and high-field sections, respectively.

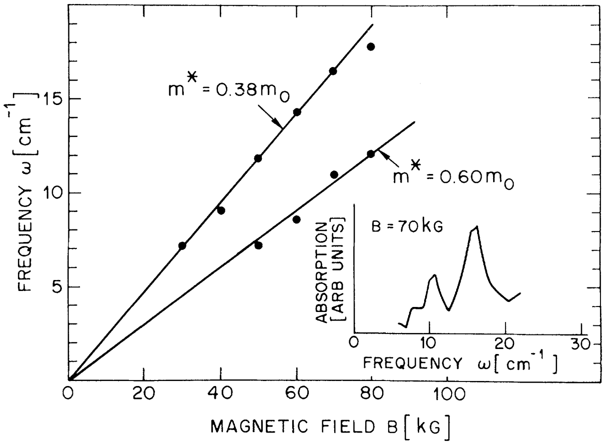

FIG. 3. Results of far-infrared cyclotron-resonance experiments on a two-dimensional hole gas. Inset: A typical spectrum at $B = 70$ kG. The graph summarizes the peak position of the absorption maxima as a function of field. m_1^* and m_2^* are the deduced effective masses.

The period of the low-field oscillations can be translated into a density $n_1 = (e/hc)s_1 = (1.95 \pm 0.02) \times 10^{11}$ cm^{-2}, leaving $n_2 = n - n_1 = (3.05 \pm 0.03) \times 10^{11}$ cm^{-2} carriers for the second subband at zero field. Using the zero-field density of states of a 2D system $D = m^*/2\pi\hbar^2$ (Ref. 1) we derive $E_{\mathrm{F}1} = 2.45 \pm 0.02$ meV and $E_{\mathrm{F}2} = 2.43 \pm 0.02$ meV, equal within the accuracy of our data. The high-field slope $s_2 = 206$ kG yields a density $n = (5.0 \pm 0.05) \times 10^{11}$ cm^2, identical to the total density. This result supports the earlier theoretical prediction[12] that at extremely high magnetic fields, magneto-oscillations[5] are merely indicative of the total electron density and not of individual subbands and their relative populations.[13,14]

The equality of the Fermi energies of the two carriers shows that both subbands are degenerate at $k = 0$. For $k \neq 0$ the two subbands are split. The splitting, which is characterized by the two different masses, $m_1^* = 0.38m_0$ and $m_2^* = 0.60m_0$, is 1.41 meV at $k = k_{\mathrm{F}} = 1.96 \times 10^6$ cm^{-1}, where k_{F} is the Fermi wave vector of the heavier band. This splitting results from a lifting of the inversion symmetry by the surface potential at the heterojunction interface. It should be noted that, in bulk GaAs, the lack of inversion symmetry has already removed the Kramers spin degeneracy of the bands for finite k. The splitting, however, is negligibly small. Here, because of the interfacial potential which quantizes the normal motion of the holes accumulated at the interface, this splitting gives rise to two well resolved subbands. Though there has been no calculation of the subband structure of 2D holes in GaAs, such calculations exist for the 2D holes in Si field-effect transistors.[2,3] These theoretical models predict that apart from $k = 0$ the lowest bound state is spin split as observed in our experiments. It is important to emphasize that this splitting does not require the existence of a magnetic field but results purely from the electric field perpendicular to the interface, its lack of inversion symmetry, and the associated effect on the spin-orbit coupling.

In summary our combined magnetotransport and cyclotron-resonance experiment shows unambiguously that the lowest hole bound state in the surface potential well at the GaAs-(AlGa)As heterojunction interface consists of two subbands, which are degenerate at $k = 0$. The lifting of the spin degeneracy at $k \neq 0$, due to the lack of inversion symmetry at the heterojunction interface, gives rise to two cyclotron masses: $m_1^* = 0.36m_0$ and $m_2^* = 0.60m_0$ at $E_{\mathrm{F}} = 2.4$ meV. The simultaneous observation of the quantized Hall effect in a two-dimensional hole system demonstrates that this novel quantum phenomenon is independent of the details of the host band structure.

We are grateful to P. M. Tedrow for the loan of his ^{3}He refrigerator and to Larry Rubin for constant technical support at the National Magnet Laboratory. We would like to thank S. J. Allen for discussions; D. V. Lang, V. Narayanamurti, and P. A. Wolff for supporting the project; and

K. Baldwin for technical assistance. Three of us (H.L.S., A.C., and D.C.T.) were guest scientists at the Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology. This work was supported in part by the U. S. Office of Naval Research, by a grant from the U. S. National Bureau of Standards, and by the National Science Foundation.

---

[1] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. 54, 447 (1982).

[2] F. J. Ohkawa and Y. Uemura, Prog. Theor. Phys., Suppl. 57, 164 (1975).

[3] E. Bangert and G. Landwehr, Surf. Sci. 58, 138 (1976).

[4] H. L. Stormer, R. Dingle, A. C. Gossard, W. Wiegmann, and M. D. Sturge, Solid State Commun. 24, 705 (1979).

[5] H. L. Stormer and W. T. Tsang, Appl. Phys. Lett. 36, 685 (1980).

[6] K. von Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. 45, 494 (1980).

[7] D. C. Tsui and A. C. Gossard, Appl. Phys. Lett. 37, 550 (1981).

[8] General Radio, type 1433-F.

[9] D. C. Tsui, A. C. Gossard, B. F. Field, M. E. Cage, and R. F. Dziuba, Phys. Rev. Lett. 48, 3 (1982).

[10] K. Hess, D. Bimberg, N. O. Lipari, H. A. Fischbach, and M. Altarelli, in *Proceedings of the Thirteenth International Conference on the Physics of Semiconductors, Rome, Italy, 1976,* edited by F. G. Fumi (North-Holland, Amsterdam, 1977), p. 142.

[11] We have used Eqs. (47) of J. C. Hensel and K. Suzuki, Phys. Rev. B 10, 4219 (1974).

[12] B. Vinter and A. W. Overhauser, Phys. Rev. Lett. 44, 47 (1980).

[13] S. Narita, S. Takeyama, W. B. Luo, S. Hiyamizu, K. Nanbu, and H. Hashimoto, Jpn. J. Appl. Phys. 20, L447 (1981).

[14] H. L. Stormer, Jpn. J. Appl. Phys. 20, L859 (1981).