Cyclotron mass of two-dimensional holes in (100) oriented GaAs/AlGaAs heterostructures

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Microwave cyclotron resonance of low-density high-mobility two-dimensional hole gases of different densities in (100) oriented GaAs/AlGaAs heterostructures has been measured at 4.2 K. The measurements show that the hole effective mass depends strongly on the confining potential. For holes in a 20 nm quantum well, the cyclotron mass decreases from $0.48m_e$ at density $p=6.9\times10^{10}/\mathrm{cm}^2$ to $0.29m_e$ at $p=0.8\times10^{10}/\mathrm{cm}^2$. The cyclotron mass for holes confined at a heterojunction is fairly insensitive to the density and has a value of approximately $0.5m_e$. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2830016]

In recent years, high-mobility two-dimensional hole systems (2DHSs) in (100) oriented GaAs/Al_xGa_{1-x}As heterostructures have been realized experimentally, either by modulation doping with carbon[1,2] or by using a field-effect transistor structure.[3,4] These device structures have been used to study 2D electron-electron interaction physics, including, for example, the 2D metal-insulator transition[5–8] and the fractional quantum Hall effect.[9] In these studies, the cyclotron mass (m^*) is one of the important material parameters, as it appears in the expression of the dimensionless interaction parameter, $r_s=(p\pi)^{-1/2}m^*e^2/4\pi\hbar^2\epsilon$, which is a measure of the strength of the Coulomb interaction in a 2DHS. Unlike m^* of electrons in GaAs/Al_xGa_{1-x}As heterostructures, which remains nearly constant, m^* of 2D holes is a function of the crystal orientation, the carrier density (p), the electric field, and the quantum confinement, due to the complex band structure of the valence bands.

While m^* of 2D holes in (311)A oriented heterostructures has been carefully measured recently,[10,11] to date, only very few experimental values of m^* in (100) oriented heterostructures are available.[12–14] Most of them were measured at relative high p (on the order of $10^{11}/\mathrm{cm}^2$) on the 2DHS in quantum wells (QWs). A systematic investigation of m^* at low p (on the order of $10^9/\mathrm{cm}^2-10^{10}/\mathrm{cm}^2$) with holes accumulating at the GaAs/Al_xGa_{1-x}As heterojunction of single interface heterostructures (SIHs), more similar to the 2DHSs employed in Ref. 5–8, is needed to more precisely determine r_s.

In this paper, we report the measurement of m^* of 2D holes in a series of SIHs, with a wide range of p, as well as three QWs with different p. The value of m^* of holes in the QWs is found to be dependent strongly on p, consistent with previous results.[14] The m^* of holes at the SIHs, on the other hand, is surprisingly insensitive to p. This difference can be qualitatively explained in terms of the confining potential of the 2D systems.

A total of eight SIH and three 20 nm QW samples have been investigated. All of the samples are (100) oriented GaAs/Al_xGa_{1-x}As heterostructures grown by molecular beam epitaxy and delta doped with carbon from the front side only. The dopant setback thickness (t) and the aluminum mole fraction (x) of the barrier layer were varied to change the carrier density. dc magnetotransport measurements were performed at 4.2 K, using standard low frequency (5–11 Hz) lock-in techniques with an excitation current of 10 nA. The density and mobility of the 2DHS are deduced from the Hall resistance and the longitudinal resistance. Cyclotron resonance was also performed at 4.2 K, in a separate cooldown, using the same technique explained in detail in Ref. 15. The microwave (28–75 GHz) frequency (f) was fixed, while the magnetic field (B) was slowly swept. The change in sample temperature, proportional to the absorbed microwave power, was monitored as a function of B. In the framework of the Drude model,[16] the absorbed power is proportional to $[1+(\omega\tau)^2+(\omega_c\tau)^2]/\{[1+(\omega_c\tau)^2-(\omega\tau)^2]^2+4(\omega\tau)^2\}$, where $\omega=2\pi f$, $\omega_c=eB/m^*$, and τ is the relaxation time. The m^* is obtained by fitting the absorption spectrum to the Drude model. We summarize in Table I the material structure, the transport characteristics, and m^* of the eleven samples used in this work.

In Fig. 1, we show the absorption spectra of three SIH and three QW samples. For the SIH samples, the position of the absorption peak shows negligible shift even though p changes by nearly a factor of 10. On the other hand, for the QW samples, the absorption peak shifts toward the low B side, indicating that m^* decreases as p decreases. Figure 2 shows the m^* obtained from Drude model fits of the data from the SIH samples and the QW samples as a function of p. For comparison, the m^* from two of the 20 nm wide QW samples measured in Ref. 14 are also included. It is clear from Fig. 2 that, for the QW samples, m^* depends strongly

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TABLE I. Sample structures, carrier densities, transport mobilities, and cyclotron masses of the samples studied in this paper.

Sample	Structure	t (nm)	x (%)	p (10^{10}/cm^2)	μ (10^3 cm^2/V s)	m^* (m_e)
1(5-22-07.1)	SIH	80	15	4.5	203	0.54
2(5-22-07.2)	SIH	120	15	3.4	160	0.54
3(5-23-07.1)	SIH	180	15	2.5	163	0.54
4(5-23-07.2)	SIH	80	32	13.1	256	0.57
5(5-24-07.1)	SIH	80	23	8.6	219	0.58
6(7-10-07.1)	SIH	270	15	1.5	168	0.50
7(7-11-07.1)	SIH	540	15	0.25	102	0.49
8(7-12-07.1)	SIH	40	15	10.4	150	0.55
9(7-10-06.1)	20 nm QW	50	16	6.9	130	0.48
10(7-10-06.2)	20 nm QW	120	16	2.2	95	0.33
11(7-11-06.1)	20 nm QW	180	16	0.8	82	0.29

on p. A linear extrapolation yields a m^* approaching $\sim 0.25m_e$ in the limit of $p=0$. On the other hand, for the SIH samples, m^* is only a weak function of p and has a value of approximately $0.5m_e$ at $p \sim 1\times 10^{10}/\mathrm{cm}^2$. This difference is possibly due to the different confining potentials in the two different structures, which can be explained using a simplified qualitative picture below.

The band structure of the valence bands is known to be complex.[17] Quantum confinement in the growth direction shifts the heavy-hole (HH) band up relative to the light-hole (LH) band. For in-plane motion, the HH states have a *smaller* effective mass than the LH states, and a crossing of the bands would occur in the absence of off-diagonal matrix elements. The anticrossing rule results in the admixture of the HH and LH bands which, in turn, gives rise to the change in m^*. Where the valence bands become highly nonparabolic depends critically on the splitting Δ between the HH and LH bands. In Fig. 3, qualitative sketches of the valence bands are shown for both the high and the low p cases in a QW and in a SIH. In the case of the QWs, the confining potential is fixed by the structure itself, i.e., the barriers of the QW. As long as p is not too high, the Hartree potential, originating from electron-electron repulsion, is small and does not contribute much to the Hamiltonian. Changing p only shifts the Fermi energy (E_F) of the 2D holes, while Δ remains nearly constant. Decreasing p moves E_F away from where the anticrossing occurs and, therefore, a smaller m^* is observed [Figs. 3(c) and 3(d)]. This is not the case for the SIH samples. When the material is extremely clean, the quantum confinement on the GaAs side results from the Hartree potential, whose strength weakens as p decreases. Therefore, at lower p, the 2D holes are less confined, Δ is smaller, and the anticrossing occurs closer to the top of the HH band. This counteracts the effect of moving E_F up [Figs. 3(a) and 3(b)]. As a result, m^* is only weakly dependent on p. While this simplified model agrees with the experimental observation qualitatively, we emphasize that the valence band structure is so complex that a comprehensive theory is needed.

The numerical value of m^* of 2D holes in (100) oriented SIH has been calculated theoretically, mostly based on the Luttinger Hamiltonian.[18–21] The main conclusion is that two values of m^* arising from spin splitting are predicted for high p (on the order of $10^{11}/\mathrm{cm}^2 - 10^{12}/\mathrm{cm}^2$). For $p < 1\times 10^{11}/\mathrm{cm}^2$, which is the focus of this paper, the two masses converge as p decreases and approach a value close to $0.15m_e$ in the $p=0$ limit. This value is very different from our experimentally observed m^*, which has a value of approximately $0.5m_e$. This quantitative discrepancy is not yet understood.

In summary, m^* of low-density 2D holes in (100) oriented heterostructures has been measured, using microwave cyclotron resonance, as a function of p. For 2D holes at SIHs, m^* has a value of $\sim 0.5m_e$ and is nearly independent of p. For 2D holes in 20 nm wide QWs, m^* decreases and approaches $\sim 0.25m_e$ as p approaches 0. The measured m^* is important in determining the Coulomb interaction parameter r_s of the 2DHS.

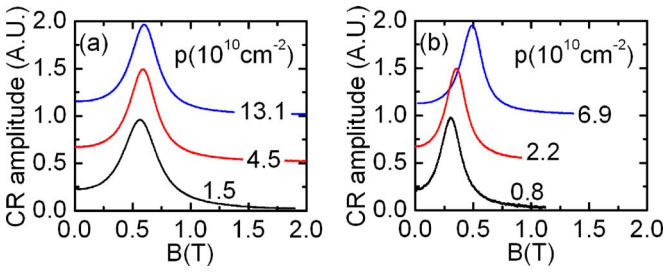

FIG. 1. (Color online) The cyclotron resonance absorption spectra of (a) SIH samples: 1, 4, and 6, and (b) QW samples: 9, 10, and 11, measured at 4.2 K. The data are shifted vertically for clarity.

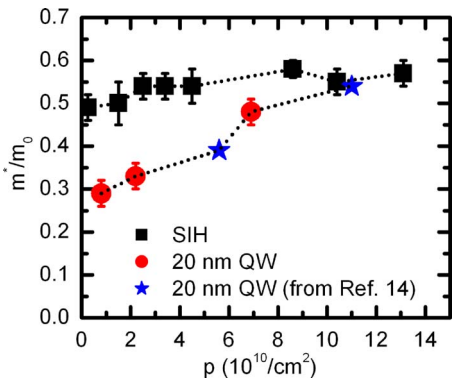

FIG. 2. (Color online) m^* as a function of p for SIHs and QWs. The dotted lines are guides for the eye. Two of the data points are from Ref. 14.

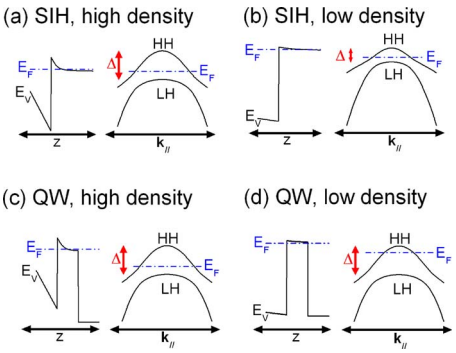

FIG. 3. (Color online) Qualitative sketch of the valence band structure in real space and k space with (a) high p and (b) low p at the SIHs, and (c) high p and (d) low p in the QWs. Δ denotes the splitting between HH and LH bands.

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[1]M. J. Manfra, L. N. Pfeiffer, K. W. West, R. de Picciotto, and K. W. Baldwin, Appl. Phys. Lett. **86**, 162106 (2005).
[2]C. Gerl, S. Schmult, H.-P. Tranitz, C. Mitzkus, and W. Wegscheider, Appl. Phys. Lett. **86**, 252105 (2005).
[3]B. E. Kane, L. N. Pfeiffer, K. W. West, and C. K. Harnett, Appl. Phys. Lett. **63**, 2132 (1993).
[4]T. M. Lu, D. R. Luhman, K. Lai, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Appl. Phys. Lett. **90**, 112113 (2007).
[5]H. Noh, M. P. Lilly, D. C. Tsui, J. A. Simmons, E. H. Hwang, S. Das Sarma, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **68**, 165308 (2003).
[6]H. Noh, M. P. Lilly, D. C. Tsui, J. A. Simmons, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **68**, 241308(R) (2003).
[7]J. Huang, D. S. Novikov, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **74**, 201302(R) (2006).
[8]J. Huang, J. S. Xia, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **98**, 226801 (2007).
[9]M. J. Manfra, R. de Picciotto, Z. Jiang, S. H. Simon, L. N. Pfeiffer, K. W. West, and A. M. Sergent, Phys. Rev. Lett. **98**, 206804 (2007).
[10]B. E. Cole, F. M. Peeters, A. Ardavan, S. O. Hill, J. Singleton, W. Batty, J. M. Chamberlain, A. Polisskii, M. Henini, and T. Cheng, J. Phys.: Condens. Matter **9**, 3163 (1997).
[11]W. Pan, K. Lai, S. P. Bayrakci, N. P. Ong, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Appl. Phys. Lett. **83**, 3519 (2003).
[12]Z. Schlesinger, S. J. AllenJr., Y. Yafet, A. C. Gossard, and W. Wiegmann, Phys. Rev. B **32**, 5231 (1985).
[13]M. Yu. Akimov, I. V. Kukushkin, S. I. Gubarev, S. V. Tovstonog, J. Smet, K. von Klitzing, and W. Wegscheider, JETP Lett. **72**, 460 (2000).
[14]H. Zhu, K. Lai, D. C. Tsui, S. P. Bayrakci, N. P. Ong, M. Manfra, L. N. Pfeiffer, and K. W. West, Solid State Commun. **141**, 510 (2007).
[15]Y. Matsuda, N. P. Ong, Y. F. Yan, J. M. Harris, and J. B. Peterson, Phys. Rev. B **49**, 4380 (1994).
[16]G. Dresselhaus, A. F. Kip, and C. Kittel, Phys. Rev. **98**, 368 (1955).
[17]R. Winkler, *Spin-Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems* (Springer, New York, 2003).
[18]D. A. Broide and L. J. Sham, Phys. Rev. B **31**, 888 (1985).
[19]T. Ando, J. Phys. Soc. Jpn. **54**, 1528 (1985).
[20]U. Ekenberg and M. Altarelli, Phys. Rev. B **32**, 3712 (1985).
[21]G. Goldoni and F. M. Peeters, Phys. Rev. B **51**, 17806 (1995).