List of Publications and Presentations

Publications

1. M. E. Sherwin, J. A. Simmons, T. M. Eiles, N. E. Harff, and J. F. Klem, "Parallel quantum point contacts fabricated with independently biased gates and a submicrometer airbridge post," *Applied Physics Letters* **65**, 2326-2328 (31 October, 1994).

Reprint removed cit

2. T. M. Eiles, J. A. Simmons, M. E. Sherwin, and J. F. Klem, "Magnetic focusing in parallel quantum point contacts," *Physical Review B* **52**, 10756-10759, (15 October, 1995).

Reprint removed

3. H. C. Chui, B. E. Hammons, N. E. Harff, J. A. Simmons, and M. E. Sherwin, "2 x 10^6 cm^2/Vs electron mobility by metalorganic chemical vapor deposition with tertiarybutylarsine," *Applied Physics Letters* **68**, 208-210, (8 January, 1996).

Reprint removed

4. J. A. Simmons, R. R. Du, M. A. Zudov, H. C. Chui, N. E. Harff, and B. E. Hammons, "Composite Fermions in 10^6 cm^2/Vs Mobility AlGaAs/GaAs Heterostructures Grown by MOCVD," in *Proceedings of the 23rd International Conf. on the Physics of Semiconductors,* edited by M. Scheffler and R. Zimmermann. Singapore: World Scientific, Vol. 3, 1996, pgs. 2511-2514.

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Sept. 23-26, 1996
St. Petersburg Russia

5. J. A. Simmons, M. E. Sherwin, M. V. Weckwerth, N. E. Harff, T. M. Eiles, W. E. Baca, H. Hou, and B. E. Hammons, "Advanced Fabrication Technologies for Nano-Electronics," in *Proceedings of the 24th State-of-the-Art Program on Compound Semiconductors*, edited by Ren, F, and S. Pearton, S. Chu, R. Shul, W. Pletschen, and T. Kamijoh. Pennington, New Jersey: The Electrochemical Society, Vol. 96-2, 1996, pgs. 186-202.

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Presentations

1. M. E. Sherwin, J. A. Simmons, J. C. Zolper, and J. F. Klem, "Advanced fabrication of mesoscopic devices in AlGaAs/GaAs," Advanced Heterostructure Workshop, Kona, Hawaii, December 4-9, 1994.

2. T. M. Eiles, J. A. Simmons, M. E. Sherwin, and J. F. Klem, "Magnetic focusing in parallel quantum point contacts," American Physical Society March Meeting, 23 March 1995, San Jose, California.

3. H. C. Chui, B. E. Hammons, N. E. Harff, J. A. Simmons, and M. E. Sherwin, "2 x 10^6 cm^2/Vs Electron Mobility By MOCVD With Tertiarybutylarsine," 37th Electronic Materials Conference, 21 June 1995, Charlottesville, Virginia.

4. J. A. Simmons, H. C. Chui, N. E. Harff, B. E. Hammons, H. Q. Hou, R. R. Du, and M. A. Zudov, "MOCVD Growth Of GaAs/AlGaAs Heterostructures For Fractional Quantum Hall Effect Studies," American Physical Society March Meeting, 18 March 1996, St. Louis, Missouri.

5. M. A. Zudov, R. R. Du, J. A. Simmons, and H. C. Chui, "Electron And Composite Fermion Transport In MOCVD-Grown GaAs/AlGaAs Heterostructures," American Physical Society March Meeting, 18 March 1996, St. Louis, Missouri.

DISCLAIMER

AC04-94AL85000

CONF-9609125--1

COMPOSITE FERMIONS IN 2 x 10^6 cm^2/Vs MOBILITY AlGaAs/GaAs HETEROSTRUCTURES GROWN BY MOCVD

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ABSTRACT

We report on our recent growth by MOCVD of 2.0 x 106 cm2/Vs mobility heterostructures. These mobilities, the highest reported to date, are attributed to the use of tertiarybutylarsine as the arsenic precursor. Measurements in tilted magnetic fields of the FQHE states near filling factor 3/2 are consistent with a spin-split composite fermion (CF) model proposed earlier. The extracted values of the product of the CF g-factor and CF effective mass agree with values previously obtained for MBE samples.

As compared to molecular beam epitaxy (MBE), metalorganic chemical vapor deposition (MOCVD) has several advantages including high quality regrowth, easily variable alloy compositions, low defect densities, and superior uniformity. However, until recently MOCVD growth has had two serious disadvantages: (1) safety concerns due to the use of highly toxic arsine gas, and (2) considerably lower material purity. The latter has meant that MOCVD-grown two dimensional electron gases (2DEGs) were too low in mobility to allow observation of the fractional quantum Hall effect (FQHE), which is easily destroyed by disorder. Because MOCVD material parameters such as impurity potential profile, defect density, uniformity, and interface quality, are possibly different from in MBE, it is worthwhile to examine the behavior of the FQHE in MOCVD material.

In this paper we report on our recent MOCVD growth[1] of high quality 2DEGs with mobilities as high as 2.0 x 10^6 cm^2/Vs at a density of 3.2 x 10^{11} cm^{-2}. These mobilities were acheived using low-toxicity tertiarybutlyarsine (TBA) as the arsenic precursor, instead of arsine. The use of TBA results in roughly a factor of two improvement in mobility. Using this material, we also studied the FQHE states near Landau level (LL) filling factor $\nu = 3/2$ in tilted magnetic fields. The data is consistent with the same spin-split composite fermion (CF) proposed earlier for MBE material by Du et al.[2] Using this model, we measure the product of the CF effective g-factor g^* and the CF effective mass m_{CF}. After taking into account the expected square root dependence[3] of m_{CF} on the external perpendicular magnetic field $B_\perp$, the measured values of $g^* m_{CF}$ for our MOCVD material are found to be in agreement with those previously obtained[2] for MBE.

The heterostructures were grown in an Emcore reactor described previously,[4] and consisted of 1 μm of undoped GaAs, an undoped $Al_{0.28}Ga_{0.72}As$ spacer of varying thickness, a ~4 x 10^{12} cm^{-2} Si delta-doping layer, 625 Å of undoped $Al_{0.28}Ga_{0.72}As$, and a 50 Å GaAs cap. Samples using both arsine and TBA as the arsenic precursor were

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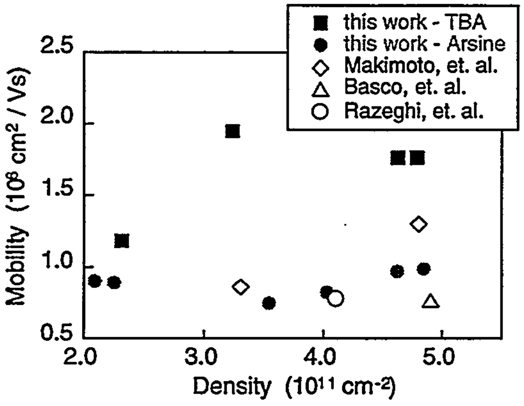

FIG. 1. Highest MOCVD mobilities to date.

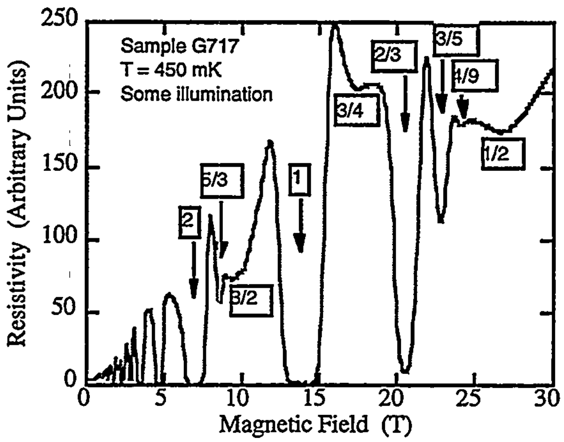

FIG. 2. R_{xx} of the 2 x 10^6 cm^2/Vs sample at 0.45 K.

grown. Mobility and density were measured via a standard lock-in technique at 0.3 K. As described elsewhere,[1] variation of the V/III ratio for arsine-grown 2DEGs caused little change in 2DEG mobility, and a cross-over in undoped bulk GaAs from p-type to n-type with increasing V/III ratios. However, for TBA-grown 2DEGs, the mobility increased for V/III ratios up to ~90, after which it leveled off, and undoped bulk GaAs remained weakly p-type for all V/III ratios measured, up to ~150. We attribute this behavior to a reduced incorporation of Si and Ge n-type impurites with the use of TBA, since typically these impurities arise from trace amounts of silane and germane in the arsine.[5] Accordingly, TBA-grown 2DEGs exhibited significantly higher mobilities and higher quality FQHE states than those grown with arsine. In Fig. 1 we plot mobility vs. density for the best MOCVD samples grown to date. While our arsine mobilities are comparable to those acheived by others,[6] our TBA 2DEGs have mobilities almost double those of all previous results based on arsine. Fig. 2 shows the longitudinal magnetoresistance R_{xx} of our highest mobility (2.0 x 10^6 cm^2/Vs) sample, at 450 mK. The FQHE states are quite strong for this temperature, and exhibit a rather low Dingle temperature of ~4 K.

In a similar TBA sample with density 2.8 x 10^{11} cm^{-2}, we studied the FQHE states around ν=3/2 in a total magnetic field B_{TOT} applied at an angle θ from normal. The sample was measured in the dark at 50 mK. Fig. 3 shows R_{xx} vs. perpendicular field $B_{\perp}$ between ν=1 and ν=2 for several θ, with the positions of the $\nu=(3p\pm2)/(2p\pm1)$ FQHE states indicated. As θ is increased, the minima associated with these ν disappear and then reappear. For example, 4/3 exhibits a strong minimum at 0°, which evolves into a maximum at 38.1°, and again becomes a minimum for θ>47°. Similar oscillatory behavior is observed for 7/5, 8/5, and 11/7. However, 5/3 remains a strong minimum for all θ.

The data can be understood in terms of the spin-split CF model of Du et al.[2] This model is similar to the standard CF model,[3] in that electrons at a $B_{\perp}$ such that ν is near 3/2 are treated as new particles, CFs, subject to an *effective magnetic field* $B_{\perp}^* = 3(B_{\perp}-B_{\perp}^{3/2})$. The FQHE of electrons near 3/2 can then be viewed as an integer QHE of the CFs due to the the effective field $B_{\perp}^*$. The energy spacing between the CF "Landau levels"

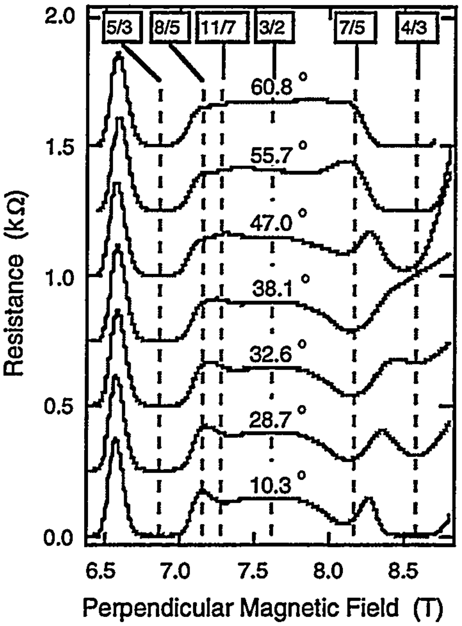

FIG. 3. R_{xx} vs. perpendicular magnetic field $B_\perp$ for several different tilt angles θ.

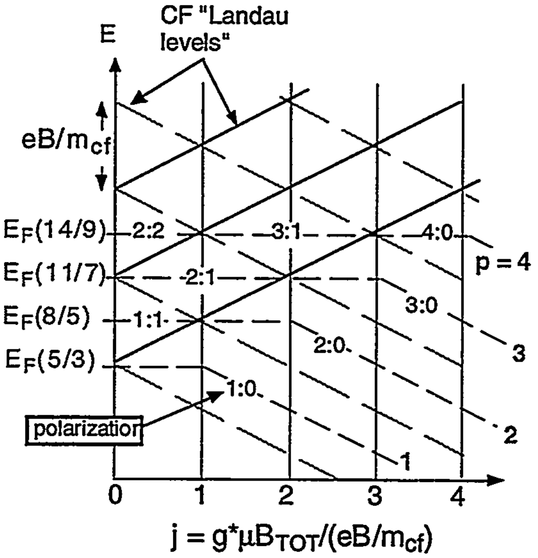

FIG. 4. Schematic of CF Landau level (LL) energies vs. Zeeman energy. When the Zeeman energy is an integer multiple j of the LL energy spacing, the levels cross, producing R_{xx} maxima.

(LLs) is thus $eB_\perp{}^*/m_{CF}$. However, the model differs from the standard one in that a finite Zeeman energy $g^*\mu B_{TOT}$, determined by the total field, is included. This results in spin-splitting of the CF LLs. By tilting the sample, $g^*\mu B_{TOT}$ can be varied while $eB_\perp{}^*/m_{CF}$ is held fixed. This situation is illustrated schematically in Fig. 4, where the CF LL energies are plotted vs. Zeeman energy. When $g^*\mu B_{TOT}$ is an integer multiple j of $eB_\perp{}^*/m_{CF}$, the CF LLs cross. Thus for a fixed electron $\nu=(3p\pm2)/(2p\pm1)$, (where p is the CF LL filling factor) the Fermi level no longer lies in an energy gap, but rather lies within a doubly degenerate CF LL. As a result, R_{xx} at a fixed ν oscillates as θ and hence $g^*\mu B_{TOT}$ is changed, with maxima appearing at integer j. Note that the 5/3 state, corresponding to $p = 1$, does not cross any CF LLs at finite B_{TOT}, and so remains a strong minimum for all θ.

To compare with this model, in Fig. 5 we plot R_{xx} vs. B_{TOT} for constant $\nu=(3p\pm2)/(2p\pm1)$. Maxima are observed for all of the states except 5/3, and their anticipated (integer) values of j are indicated. In the upper part of Fig. 6 we summarize this data by plotting the observed positions of the maxima in the B_{TOT} - $B_\perp{}^*$ plane. In this plane, integer values of j appear as lines emanating from the origin, and are determined by the data points. (A single j=2 line is drawn for the 8/5 and 11/7 states, which give good agreement.) The spin polarizations of each FQHE state as a function of B_{TOT} are indicated by the labeled vertical lines. The lower part of Fig. 6 plots the same data in a different manner. Because $jB_\perp{}^*/B_{TOT} = g^*m_{CF}/2m_0$, the position of each data point in the B_{TOT} - $B_\perp{}^*$ plane gives a measure of g^*m_{CF}, which is plotted as a function of $B_\perp{}^*$. A linear fit to the data yields $g^*m_{CF}/2m_0 = 0.216 \pm 0.016\ (\mathrm{T}^{-1})B_\perp{}^*$.

Our measured value for $g^*m_{CF}/2m_0$ is much higher than that previously obtained[2] for an MBE sample, but our density is also much higher. Since m_{CF} scales as $(B_\perp)^{1/2}$, in

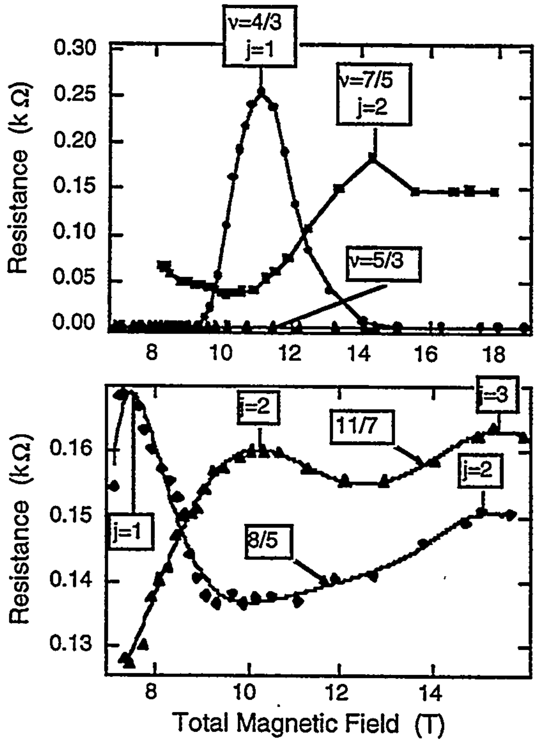

FIG. 5. R_{xx} at fixed ν=(3p±2)/(2p±1) as a function of total field B_{TOT}.

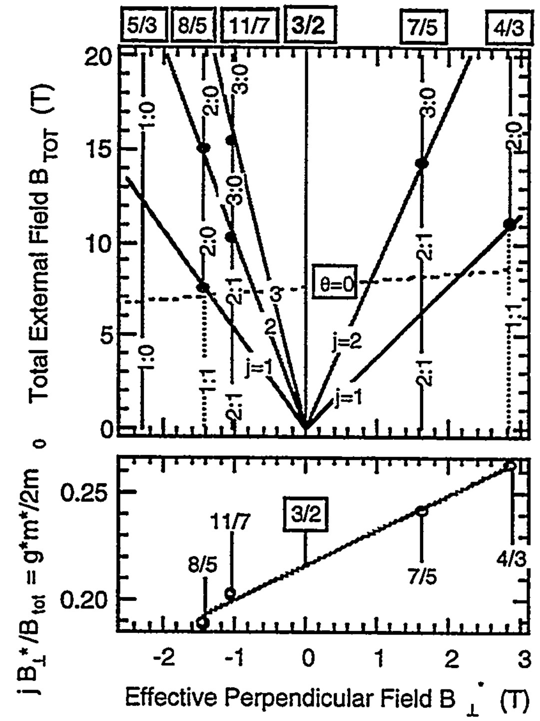

FIG. 6. Upper: Positions of R_{xx} maxima in the B_{TOT}-$B_\perp$* plane. Lower: g^*m_{CF} values extracted from the data, and a linear fit. See text.

order to make a comparison the first term in our measured $g^*m_{CF}/2m_0$ must be scaled by $(B_\perp)^{-1/2}$, while the second term, which contains B*, must be scaled by $(B_\perp)^{1/2}$. Using a scaling factor of 1.58 we obtain a scaled value of 0.137 + 0.025(T^{-1})$B_\perp$*, which agrees within experimental error with the value obtained earlier for MBE, 0.132+ 0.023(T^{-1})$B_\perp$*.

Acknowledgment—This work supported by the U.S. Dept. of Energy under Contract DE-AC04-94AL85000.

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