Fractional Quantization in ac Conductance of $Al_xGa_{1-x}As$ Capacitors

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(Received 12 December 1985)

Minima are found in the ac conductance (100 kHz) of n^--GaAs–$Al_xGa_{1-x}As$–n^+-GaAs capacitors at voltages corresponding to fractional fillings, $\frac{1}{3}$ and $\frac{2}{3}$, of the lowest spin-split Landau level of an accumulation layer on n^--GaAs. These are the first observations of a fractional quantum effect in which electron motion is perpendicular rather than parallel to the n^--GaAs/$Al_xGa_{1-x}As$ interface.

PACS numbers: 71.50.+t, 72.20.Fr, 73.40.Gk, 73.40.Ty

The fractional quantum Hall effect (FQHE) is characterized by the observation of plateaus in the Hall resistivity ρ_{xy} of a two-dimensional electron gas, and the simultaneous vanishing of the diagonal resistivity ρ_{xx}, at values of the electron density N_S where the filling factor ν becomes a fraction p/q ($p=1,2,3,\ldots$ and $q=3,5,7$).[1,2] The filling factor ν is defined by $\nu = N_S h/eB$ where h is Planck's constant, e is the electron charge, B is the magnetic induction, and eB/h, the degeneracy of a spin-split Landau level, is $2.42\times10^{10}/\mathrm{cm}^2\cdot\mathrm{T}$. Minima at $\nu=\frac{1}{3}$ and $\frac{2}{3}$ are most pronounced in the FQHE. Most observations of the FQHE have been made on modulation-doped GaAs/$Al_xGa_{1-x}As$ structures grown by molecular-beam epitaxy in which electrons from heavily doped $Al_xGa_{1-x}As$ populate an inversion layer in GaAs at the GaAs/$Al_xGa_{1-x}As$ interface. The carrier concentration N_S is fixed by preparation conditions; observation of the FQHE requires the sweeping of B in order to change ν. The FQHE is only observed at temperatures below ~ 3 K.

We have recently shown that n^--GaAs–$Al_xGa_{1-x}As$–n^+-GaAs (AlGaAs) capacitors that use undoped $Al_xGa_{1-x}As$ as a barrier dielectric between GaAs layers are nearly ideal for the study of tunneling. Structure in current-voltage (I-V) curves due to resonant Fowler-Nordheim (FN) tunneling is observed when the $Al_xGa_{1-x}As$ thickness is about 35 nm or less.[3] Direct tunneling occurs when the $Al_xGa_{1-x}As$ layer is about 20 nm thick.[4] When AlGaAs capacitors are biased with the n^+-GaAs gate positive an accumulation layer forms on the n^--GaAs substrate as shown schematically in the inset of Fig. 1. Electrons in the accumulation layer form a two-dimensional electron gas. In high magnetic fields structure in dc I-V, in ac capacitance-voltage (C-V), and in ac conductance-voltage (G-V) curves reflects the formation and filling of Landau levels in the accumulation layer.[4] In contrast to modulation-doped heterostructures the occupation of the accumulation layer in n^--GaAs can be changed from 0 to $>1\times10^{12}/\mathrm{cm}^2$ by a change in the gate voltage V_G. I report here measurements on AlGaAs capacitors in magnetic fields high enough that all carriers induced in the accumulation layer on n^--GaAs by gate voltages $V_G \lesssim 0.35$ V are in the lowest magnetic quantum level ($\nu \leqslant 1$). Minima occur in ac conductance-voltage curves at gate voltages corresponding to $\nu=\frac{1}{3}$ and $\nu=\frac{2}{3}$ which I believe are manifestations of minima in the density of states at fractional fillings of the lowest Landau level in the extreme quantum limit.

The n^--GaAs–undoped $Al_xGa_{1-x}As$–n^+-GaAs wafer used in the present work is the same as used in Ref. 3. It was grown by molecular-beam epitaxy on a single-crystal n^+-GaAs substrate.[5] Capacitors of

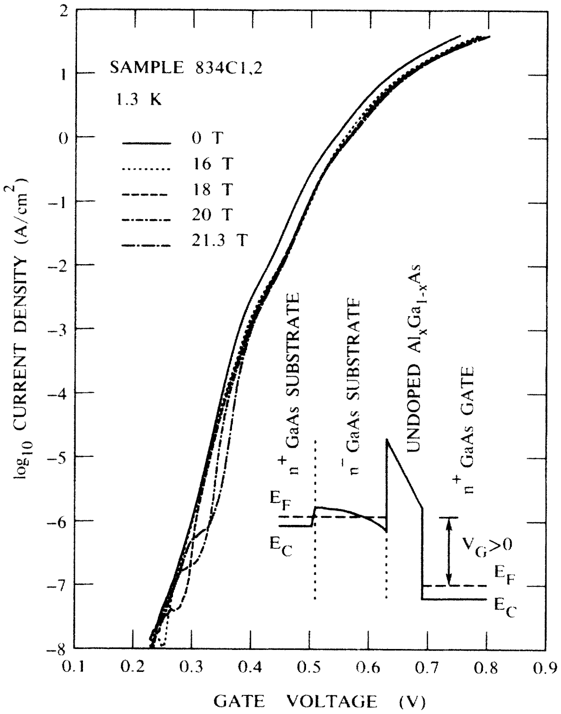

FIG. 1. Logarithm of dc current density vs gate voltage for n^--GaAs–undoped $Al_xGa_{1-x}As$–n^+-GaAs capacitor at different magnetic fields. Undoped $Al_xGa_{1-x}As$ thickness is ~ 31 nm. Inset: Schematic energy-band diagram for positive V_G showing formation of accumulation layer on n^--GaAs.

known area were formed after molecular-beam epitaxy by the etching of a mesa with the metal contact as an etch mask. The AlAs mole fraction in undoped $Al_xGa_{1-x}As$ is estimated as $x \sim 0.32$ from measurements of the barrier height at the $Al_xGa_{1-x}As/n^+$-GaAs interface.[6] C-V and I-V measurements indicate that conduction is uniform over the sample area. At 0 T and 77 K capacitance and current density are proportional to sample area. The thickness of the $Al_xGa_{1-x}As$ derived from analysis of resonant FN tunneling curves, ~ 31 nm, is consistent with sample thickness derived from C-V curves.[3] Procedures for measuring I-V, C-V, and G-V curves have been described.[4] The Hewlett-Packard model 4274A *LCR* meter used for C-V and G-V curves measures the impedance of the AlGaAs capacitor and converts it to a parallel capacitance, C, and conductance, G. C-V and G-V curves are measured at 100 kHz by use of an ac modulation voltage of 0.004 V rms. The dc voltage step is 0.005 V for all measurements.

dc current-voltage curves for sample 834C1,2 at 1.3 K and at different magnetic fields perpendicular to the sample are shown in Fig. 1. Sample 834C1,2 is thick enough that direct tunneling of electrons does not occur. Instead, V_G must exceed the barrier height at the n^+-GaAs/$Al_xGa_{1-x}As$ interface, 0.24 V, before tunneling currents are above noise. At 0 T, modulation of the I-V curve is due to resonant FN tunneling.[3] As the magnetic field increases above 16 T there is a pronounced decrease in tunneling current for $V_G \cong 0.3$ V; the decrease is larger and is shifted to higher voltages for larger values of B.

The nature and extent of the structure in I-V curves due to the magnetic field is shown in Fig. 2 in which the difference of the logarithms of the current density in magnetic field B, $J(B)$, and in zero magnetic field, $J(0)$, is plotted as a function of gate voltage for two different values of B. C-V and G-V curves at the same temperature and magnetic fields are also plotted. The effect of magnetic field on the magnitude of dc current is large. At 21.3 T and 0.355 V there is more than an order of magnitude decrease in current density due to the magnetic field. The steep minimum in the I-V curves at 0.255 V in Fig. 2(a) and at 0.355 V in Fig. 2(b) occurs at $\nu = 1$, the completion of the occupation of the first spin-split Landau level. For these minima the full width at half minimum of the difference of I-V curves is proportional to B. The position of the minimum at 0.48 V in the I-V curves in Figs. 2(a) and 2(b) is nearly independent of B; it may be connected with FN tunneling which is the dominant dc conduction mechanism above 0.24 V.

The C-V curves below 0.38 V in Fig. 2 are strongly suppressed because of the high resistance of the n^--GaAs substrate due to magnetic freezeout of donors.[4,7] Only as dc tunnel currents through the $Al_xGa_{1-x}As$ dielectric exceed 10^{-3} A/cm^2 at $V_G \geq 0.35$ V does the capacitance increase and approach the value of capacitance in accumulation in zero magnetic field, 96 pF. ac G-V curves in Fig. 2 are plotted on a logarithmic scale because of the wide range of conductance values. The magnitude of ac conductance is also reduced by series resistance at high magnetic fields but not as extensively as capacitance is reduced. Even when the magnitude of conductance decreases, the shape of the curve is unchanged. At 16 T the minimum in the G-V curve at 0.25 V coincides with the minimum of the I-V curve. At 21.3 T the minimum occurs at lower voltage than for the I-V curve. This is because there are two factors contributing to ac conductance. One contribution arises from filling and emptying of states in the accumulation layer by electrons flowing from the n^+-GaAs substrate through the n^--GaAs substrate into the accumulation layer. The second contribution comes from FN tunnel current through the $Al_xGa_{1-x}As$ barrier. The first contribution dominates below ~ 0.35 V; the second is responsible for the steep rise in conductance at higher voltages. There is no contribution to ac conductance due to dc tunneling through the $Al_xGa_{1-x}As$ barrier for $V_G \leq 0.3$ V since tunnel currents are less than 10^{-8} A. Visible in the G-V curve are minima at volt-

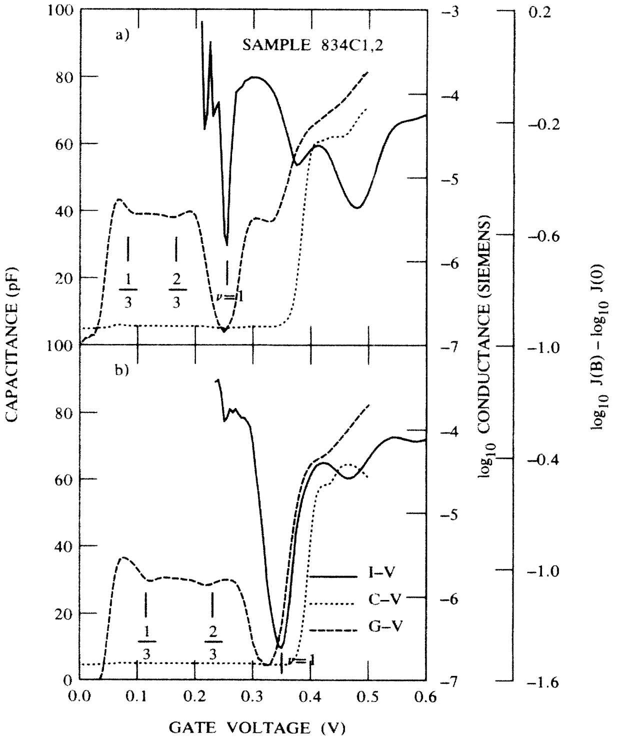

FIG. 2. $\log_{10}J(B) - \log_{10}J(0)$ (I-V), capacitance (C-V), and logarithm of conductance (G-V) vs V_G at 100 kHz and 1.3 K, at different constant magnetic fields: (a) $B = 16$ T. (b) $B = 21.3$ T.

ages close to $\frac{1}{3}$ and $\frac{2}{3}$ of the voltages corresponding to $\nu = 1$. I propose that these are manifestations of minima in the density of states due to a fractional quantum effect. Comparable minima occur in C-V curves but are less well resolved than in G-V curves because magnetic freezeout depresses the values of capacitance to a low level. The connection between capacitance and density of states is quite direct,[8] but the relation is less clear for ac conductance. G is the loss related to charging of the AlGaAs capacitor; it is not a direct, quantitative probe of the single-particle density of states of the free carriers in the accumulation layer of the sample but does appear to be proportional to the density of states.

The determination of voltages corresponding to $\nu = \frac{1}{3}$ and $\frac{2}{3}$ depends on determination of the threshold voltage, V_T, the minimum gate voltage to establish an accumulation layer at the n^--GaAs-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ interface, since the surface concentration N_S is approximately proportional to $V_G - V_T$. Structure due to the effect of Landau levels on C-V, G-V, and I-V curves can determine V_T. In Fig. 3(a) a fan diagram of the voltages for minima of C-V and G-V curves corresponding to the first Landau level minimum and to the first spin-split minimum is plotted as a function of magnetic field. Values of minima for C-V and G-V curves coincide within 0.005 V. Minima in C-V and G-V are readily determined up to $V_G \sim 0.3$ V; above that voltage dc tunneling currents interfere with the use of C-V and G-V curves for the fan diagram. Also plotted in Fig. 3(a) are minima from dc I-V curves such as in Fig. 2. They agree well with ac measurements and extend the fan diagram to higher gate voltages. dc currents are low enough that they are not affected by magnetic freezeout of the substrate. The threshold voltage, V_T, is 0.005 V from the intercept of Fig. 3(a). For an ideal AlGaAs capacitor V_T should equal the difference in Fermi levels of the n^--GaAs and n^+-GaAs layers, approximately -0.080 V for this sample. However, negative charge in the undoped $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ shifts both C-V curves and V_T to positive voltages.[6] In Fig. 3(b), the ratio $(V_M - V_T)/(V_S - V_T)$ is plotted as a function of B where V_M is the voltage for minima in ac conductance and V_S is the voltage for $\nu = 1$, derived from dc tunneling curves. Also drawn are dashed lines corresponding to $\nu = \frac{1}{3}$ and $\frac{2}{3}$. The constancy of the ratios $\nu = \frac{1}{3}$ and $\nu = \frac{2}{3}$ for the data is good and shows the existence of a fractional quantum effect.

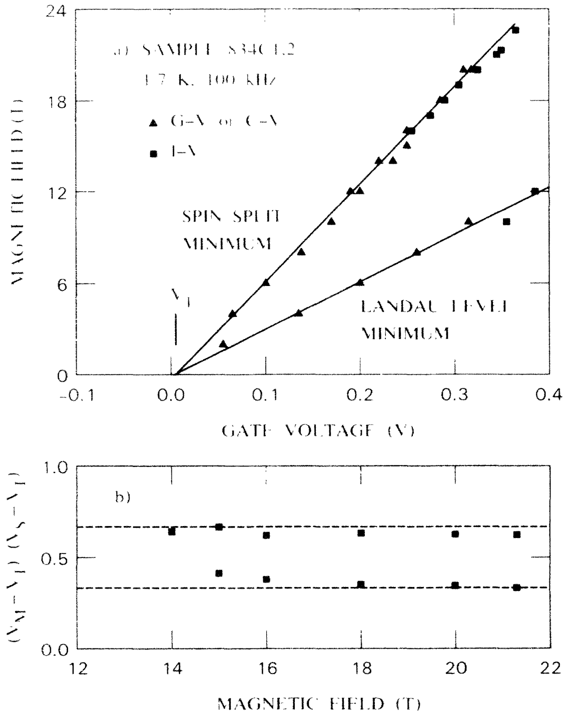

FIG. 3. (a) Fan diagram of the minima of C-V, G-V, or $[\log_{10}J(B) - \log_{10}J(0)]$-$V$ curves. (b) Fractional occupancy of lowest Landau level corresponding to minima in G-V curves at different magnetic fields. $T = 1.3$ K. The dashed lines are at $\nu = \frac{1}{3}$ and $\frac{2}{3}$.

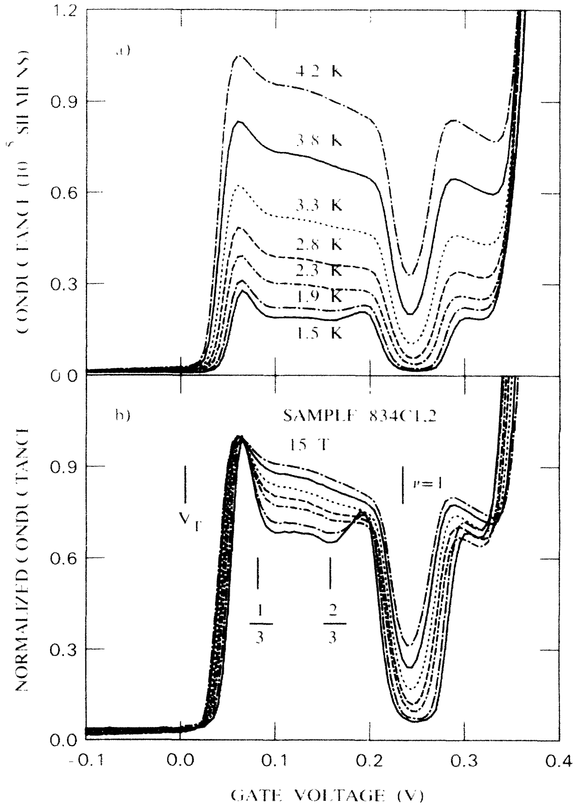

FIG. 4. (a) ac conductance (100 kHz) of AlGaAs capacitor vs gate voltage at different sample temperatures. (b) ac conductance of AlGaAs capacitor normalized to first maximum for different sample temperatures.

The temperature dependence of the ac conductance has been measured at 15 T, at 10 kHz, and at 100 kHz. In Fig. 4(a) conductance at 100 kHz of the sample at different temperatures is plotted on a linear scale. For all curves there is steep rise to a maximum in ac conductance above V_T. At lower temperatures the magnitude of ac conductance at all voltages decreases, presumably because of increased resistance of the n^--GaAs substrate due to magnetic freezeout of donors. To compare curves at different temperatures, ac conductance curves are normalized to the first maximum and are plotted in Fig. 4(b). Figure 4(b) also shows V_T and $\nu = 1$ extrapolated from dc tunneling curves at higher magnetic fields. A minimum at $\nu = \frac{2}{3}$ is barely observable in the curve measured at 2.8 K but becomes more pronounced as the temperature is lowered. Minima at $\nu = \frac{1}{3}$ are not as well resolved at 15 T as at higher values of B and are shifted to slightly higher voltages by overlap of the initial maximum conductance peak. However, the qualitative temperature dependence corresponds to that observed for the FQHE. Similar structure in ac conductance is observed at 10 kHz. No structure that corresponds to other odd fractions p/q has been observed in AlGaAs capacitors; however, ac conductance minima have been observed at $\nu = \frac{1}{3}$ and $\nu = \frac{2}{3}$ in samples that show direct tunneling. The structure is not as well resolved as in the present sample in which there is no dc tunnel current for voltages at which structure occurs in ac conductance at fractional filling of the lowest Landau level.

In measurements on AlGaAs capacitors at constant magnetic field a pattern of Landau levels with a continuous range of density of states is established for the accumulation layer by the magnetic field. By a change in V_G of an AlGaAs capacitor, electrons flow to or from the n^+-GaAs substrate and change the number of electrons in the accumulation layer; the Fermi level moves through the varying density of states as N_S changes. Structure in magnetotunneling from accumulation layers, whether measured by I-V, C-V, or G-V curves, is particularly sensitive to minima in the density of states in the accumulation layer as shown in this work and previously.[4] It is believed to involve only current flow normal to the interface, not transport along the two-dimensional electron gas of the accumulation layer. For modulation-doped heterostructures, on the other hand, observation of a FQHE in ρ_{xx} and ρ_{xy} depends on both the density of states and electron transport parallel to the inversion layer at the GaAs/Al$_x$Ga$_{1-x}$As interface.

We have here the first evidence of a fractional quantum effect that does not rely on conventional transport within the two-dimensional electron layer. It is the first example of a fractional quantum effect in a gated GaAs/Al$_x$Ga$_{1-x}$As heterostructure though FQHE has been observed in gated Si metal-oxide-semiconductor field-effect transistors.[9] The observation of minima in ac conductance at $\nu = \frac{1}{3}$ and $\nu = \frac{2}{3}$ suggests a decrease in the density of states in the lowest spin-split Landau level at these fractions. Theories of the FQHE imply that there is an energy gap in the spectrum of charge-carrying excitations of an electron liquid at $\nu = \frac{1}{3}$, with excitations being those of fractionally charged particles.[10] ac conductance and dc tunneling measurements involve single electrons moving in and out of the lowest Landau level. It is not clear what the connection is between a minimum in the single-particle density of states at $\nu = \frac{1}{3}$ or $\frac{2}{3}$ and an energy gap for fractionally charged quasiparticle excitations.

This work would not have been possible without the samples provided by H. Morkoç. The superconducting magnet used was made available through the courtesy of F. F. Fang. Portions of this work were done while the author was a visiting scientist at the Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology.

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