Fate of the Delocalized States in a Vanishing Magnetic Field

I. Glozman, C. E. Johnson, and H. W. Jiang
Department of Physics, University of California at Los Angeles, Los Angeles, California 90024
(Received 2 June 1994)

We present an experimental study of the fate of the delocalized states as $B \to 0$ in a disordered two-dimensional electron gas system. Evolving peaks in the longitudinal conductivity σ_{xx} are used to map out the delocalized states in the density–magnetic-field plane. We demonstrate unambiguously that the energy of the lowest delocalized-state band not only deviates from the "traditional" Landau level center, but also floats up above the Fermi level as $B \to 0$.

PACS numbers: 73.40.Hm, 71.30.+h

The existence of delocalized (extended) states is an essential ingredient in the theory of the quantum Hall effect. As has been well established for some time now that the energy of a delocalized-state band or level in a quantum Hall system is centered around its respective Landau levels $E_p = (p + 1/2)\hbar\omega_c$ in the high-magnetic-field limit. However, since it is believed that at $B = 0$ all states should be localized in a 2D system [1], a profound question concerning the fate of the delocalized states as $B \to 0$ *arose* [2] soon after the discovery of the quantum Hall effect. About a decade ago, Khmelnitskii [3] and Laughlin [4] both argued on theoretical grounds that such delocalized states, in the presence of strong disorder, cannot disappear discontinuously as $B \to 0$ but must rather "float up" in energy above the Fermi level. Unfortunately, since conventional quantum Hall devices are only weakly localized, with delocalized states well below the Fermi level even at $B = 0$, this fundamentally important idea has not been experimentally verifiable and has received diminishing attention in recent years.

Very recently, Kivelson, Lee, and Zhang [5] incorporated this idea into a Chern-Simons-Ginzburg-Landau formalism and proposed a global phase diagram (GPD) of the quantum Hall effect in the disorder–magnetic-field plane. With a strong promise of experimentally verifiable predictions in both integer and fractional quantum Hall effect regimes, the GPD has certainly caused a renewal of interest in this particular issue. Experimentally, a transition from an insulator at $B = 0$ (where all states the are localized below E_F) to a quantum Hall conductor at finite B has been demonstrated in disordered 2D electron gas (2DEG) systems first by Jiang *et al.* [6] and subsequently by Wang *et al.* [7] and by Hughes *et al.* [8]. Nevertheless, these experiments, though consistent with the particular topology of the GPD, do not rule out other possibilities and certainly do not constitute direct evidence of floating. In addition to the hypothesis of Khmelnitskii and Laughlin, one could imagine, for instance, that as $B \to 0$ the delocalized states simply disappear *below* the Fermi level without ever rising above it. Alternatively, the delocalized states from different Landau levels could possibly merge before floating.

In a recent experiment, Shashkin *et al.* [9] claimed to have observed the *floating* and *combining* of the delocalized states from all Landau levels for $B \to 0$. An arbitrary criterion of $\sigma_{xx} = e^2/20h$ was used to map out the metal-insulator phase boundary. This cutoff value is conceptually troublesome, and not a *a priori* justifiable, particularly at low B. Their results do not at all suggest floating with respect to the Fermi level and are consequently inconsistent with the recently observed insulator–quantum Hall conductor–insulator delocalization transition [6–8]. In this respect, it is also inconsistent with the global phase diagram, as it implies a direct metal–quantum Hall conductor transition.

With a view toward resolving these issues, the present work represents a systematic study of the delocalized states in a finite magnetic field by measuring evolving peaks in the longitudinal conductivity σ_{xx}. In mapping out the diagram of the delocalized states, we will present strong evidence supporting the following view: In the transition from the spin-degenerate quantum Hall conductor state at $\nu = 2$ to the Anderson insulator as $B \to 0$, the lowest delocalized-state band neither disappears nor merges with those at higher energies below the Fermi level but rather *floats* up continuously, piercing the Fermi surface.

The sample used in the present work was a modulation-doped GaAs/AlGaAs heterostructure fabricated by molecular beam epitaxy (MBE). The active 2DEG layer was formed on top of a Si-doped AlGaAs layer without the conventional undoped spacer to ensure a large random fluctuation of the impurity potential and thus a low mobility ($\sim 4 \times 10^4$ cm^2/Vs at $T = 25$ mK) at a density of $n = 4.6 \times 10^{11}$/cm^2. Under high gate voltage, corresponding to a low Fermi energy, the 2DEG is strongly localized as described elsewhere [6,10]. A Hall-bar pattern of size 1 mm × 3 mm was etched out by standard lithographic techniques and a NiCr gate was evaporated onto its surface.

The magnetotransport measurements were carried out by standard low-frequency lock-in techniques, typically at an excitation frequency of 13 Hz. Where the out-of-phase component was non-negligible, the frequency was

 0031-9007/95/74(4)/594(4)$06.00

adjusted accordingly. Excitation currents never exceeded 10 nA; however, where non-Ohmic effects were detected, lower currents were used. Most of our experiment was conducted in the National High Magnetic Field Laboratory. The samples were placed in the mixing chamber of a dilution refrigerator, which allowed us to obtain temperatures between 25 and 500 mK. A magnetic field up to 18 T was applied normal to the 2DEG plane by a superconducting solenoid. Although qualitatively similar results were obtained for two different-density samples, for the sake of clarity, we present only the data corresponding to the lower-density one.

We used peaks in the longitudinal conductivity σ_{xx} to track the phase boundaries (the delocalized states) between two quantum Hall conductors and between quantum Hall conductor and insulator. As has been generally accepted, a σ_{xx} peak at low temperatures corresponds to the zero-temperature mobility edge (a metallic point with no temperature dependence as $T \rightarrow 0$) in the continuous phase transition between two quantum Hall conductors [11]. Such a metallic point is also expected when the Fermi level crosses the delocalized states in the insulator–quantum Hall conductor transition [5]. Temperature-independent points in ρ_{xx} have, in fact, been observed in the context of the insulator–quantum Hall conductor phase transitions driven by a magnetic field [6,7]. Furthermore, it has also been shown that the metallic point manifests itself as a peak in σ_{xx} [8] with a possibly universal value of e^2/h, in the spin-degenerate case.

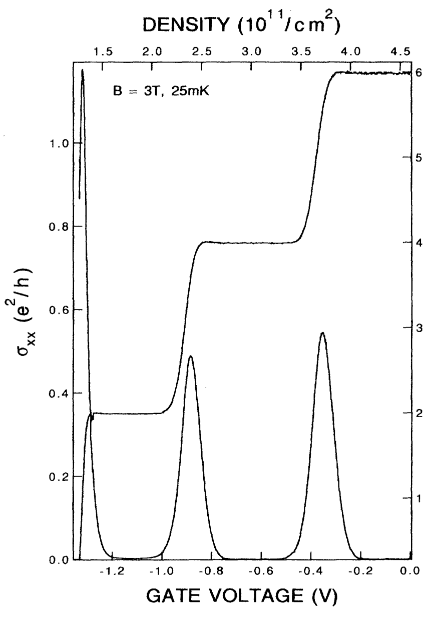

FIG. 1. Typical trace of σ_{xx} and σ_{xy} vs V_g at fixed B used to map out the delocalized states. A peak in σ_{xx} is assumed to result when E_F crosses a delocalized state, identifiable by the value of σ_{xy} on either side of the peak. Each peak adds one point to the n-B phase diagram in Fig. 2.

Figure 1 shows a typical trace used to map out the delocalized states in a finite magnetic field, for which the quantum Hall effect is well resolved. Both the σ_{xx} and σ_{xy} curves were derived numerically from the raw data of ρ_{xx} and ρ_{xy}. As the density (gate voltage) is changed at a fixed B, E_F sweeps through the peaks and valleys in the density of states. Each peak in σ_{xx}, at a given density and magnetic field, corresponds to the occupation by E_F of a delocalized-state energy band and yields one point to the n-B phase diagram. Density as a function of the gate voltage is obtained experimentally both from the measurement of the Hall resistance and from the period in the Shubnikov–de Haas oscillation in the magnetic-field sweeps at fixed gate voltages. The n vs V_G curve shows a simple linear relation as expected for a capacitive gate.

Figure 2 shows the phase diagram of the delocalized states produced using this method. The lowest level represents the quantum Hall conductor-insulator phase boundary. As the peaks becomes very narrow at a low temperature of 25 mK, any uncertainty of the peak position becomes negligibly small. Ideally, one would like to measure the energy of the levels directly. While this is not possible in a magentotransport experiment, the zero-field Fermi energy E_F is fortunately not expected to be significantly affected by a weak magnetic field, roughly when $\omega_c \tau \sim 1$ and the Landau levels are sufficiently smeared. Indeed, this is precisely the region where theory predicts floating.

In the opposite extreme, in the high B or low disorder limit, the filling factor of a peak is given exactly by the average value of the filling factors of the two adjacent quantum Hall conductors [12] or, equivalently,

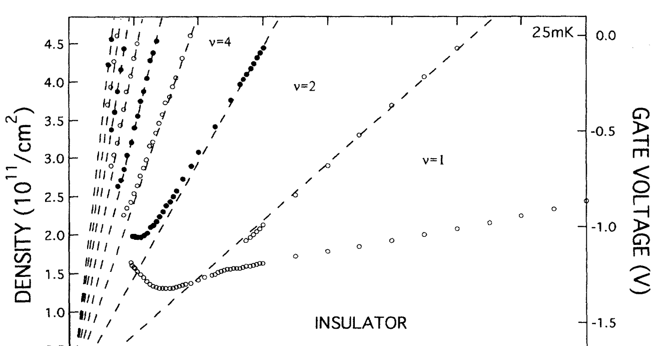

FIG. 2. Floating of the lowest delocalized state is shown here in the context of the delocalized states in the n-B plane. Quantum Hall conductor regions are labeled with appropriate filling factors or values of $\sigma_{xy}/(e^2/h)$, and are separated by metallic delocalized states. The energy of these delocalized states can be considered directly proportional to n in the data region. Dotted lines represent the traditional Landau levels, with both spin states plotted for the lowest level.

E_F coincides with a Landau level (indicated by the dashed lines in Fig. 2). Therefore, the energy levels in this diagram can be considered directly proportional to the density via the free-electron expression $E_F = \pi\hbar^2 n/m$. A striking feature of this diagram is the upward curvature of the lowest energy level, clearly exhibiting floating behavior and showing that there is no merging with the higher levels, at least in the region studied. The diagram even suggests that some deviation from linearity may be taking place in the second level as well.

It must be noted that the predominant floating feature occurs for the lowest level, consistent with a greater effective disorder at lower densities. Increasing disorder is, of course, an essential ingredient, as far as floating is concerned, according to Laughlin's *gedanken* experiment [4]. A structure around $B \approx 5$ T seems to initiate a possibly Zeeman-like level splitting to a resolved quantum Hall conductor phase at $\nu = 1$ for $B > 6$ T.

Figure 3 explicitly shows the evolution of the lowest level, as the corresponding peak in σ_{xx} clearly reverses direction (i.e., floats), with respect to the density, flattening out in the process. Error bars on the lowest level, shown explicitly in Fig. 4, are meant to imply that the peak becomes progressively more difficult to resolve in a decreasing magnetic field. Our experiment at a higher temperature of 300 mK indicates that our phase diagram is fairly insensitive to temperature (well within the error bars), as expected for metallic delocalized states. In fact, unlike the peaks in σ_{xx} used to map out the delocalized states, any peaks observed in the insulating phase are not constant in value but rather go to zero exponentially with temperature. For $B < 1.9$ T, the peak corresponding to the lowest level can no longer be resolved; a lower temperature may, however, push the cutoff magnetic field to a somewhat lower value. All that can be said at present is that at $B = 0$ a weakly localized high-density regime is separated from a strongly insulating low-density one by a "fuzzy" boundary around $n = 1.8 \times 10^{11}/\mathrm{cm}^2$.

The nonmonotonic dependence of the density on B implies that, for some fixed density around $n = 1.5 \times 10^{11}/\mathrm{cm}^2$, the lowest delocalized state first sinks down, entering the Fermi sea on the high field side, and subsequently floats upward, leaving the Fermi sea in a decreasing B. A horizontal sweep in B at constant density around this region leads to an insulator–quantum Hall conductor–insulator transition consistent with theory [5] and several recent experiments [6–8]. This clearly establishes, for the first time, the nature of the delocalization transition, as arising from a floating of the lowest delocalized level.

We have also attempted to determine the lowest phase boundary via a fixed value of σ_{xx}, the criterion used by Shaskin *et al.* [9]. We found in the low field limit, right around the field where Fig. 2 starts to show a deviation, this so-called phase boundary begins to flatten out and continues in this manner towards $B = 0$. We therefore believe that curve reflects, not a fundamental zero-temperature mobility edge, but rather an arbitrary

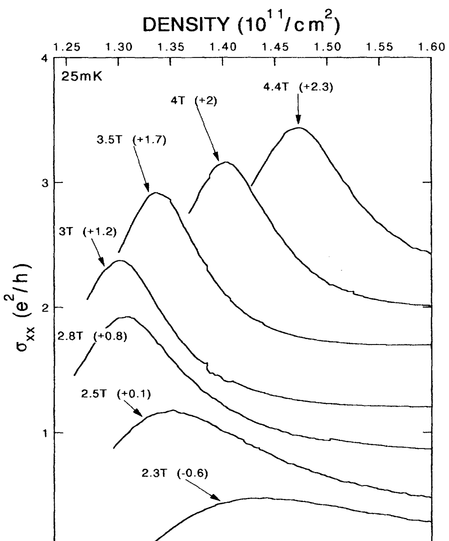

FIG. 3. The peak in σ_{xx} corresponding to the lowest delocalized states is shown at several values of B and is clearly seen to reverse direction with respect to density as $B \rightarrow 0$. For the purpose of illustration, the peaks are offset vertically by the values, in units of e^2/h, shown in parentheses.

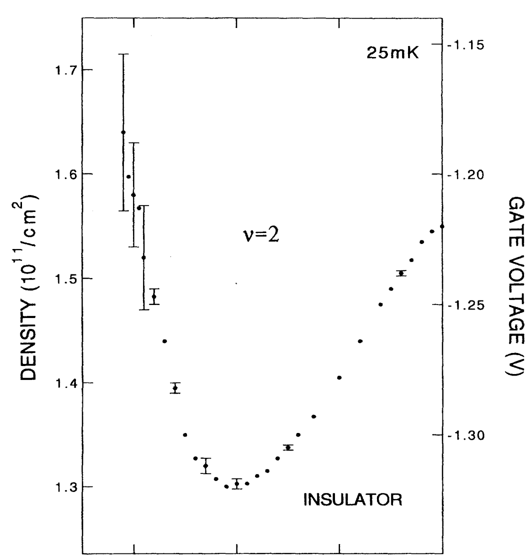

FIG. 4. Phase diagram for the lowest delocalized state, derived from the peaks in σ_{xx}, as in Fig. 3, unequivocally demonstrates floating. Error bars suggest the diminishing resolvability of the peak as $B \rightarrow 0$ and represent a reasonable uncertainty in the peak position.

cross section through the parameter space of σ_{xx}, in the insulating regime. Finally, in preliminary studies with high mobility ($\sim 1.5 \times 10^6$ cm^2/Vs) samples, no floating has been observed for B as low as 0.1 T.

In conclusion, we have mapped out a phase diagram of the delocalized states in a disordered quantum Hall system, and have demonstrated experimentally that the lowest level of the delocalized states does not disappear below E_F, but rather floats above it as $B \rightarrow 0$.

We would like to thank S. Kivelson, H. L. Stormer, and J. Rudnick for invaluable discussions, as well as W. Schaff for MBE samples. This work is supported by the NSF under Grant No. DMR-93-13786, and by the State of Florida through the National High Magnetic Field Laboratory. H. W. J. also would like to acknowledge support by the Alfred Sloan Foundation.

[1] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramarkrishnan, Phys. Rev. Lett. **42**, 673 (1979).
[2] B. I. Halperin, Phys. Rev. B **25**, 2185 (1982).
[3] D. E. Khmelnitskii, Phys. Lett. **106**, 182 (1984); JETP Lett. **38**, 556 (1983).
[4] R. B. Laughlin, Phys. Rev. Lett. **52**, 2304 (1984).
[5] S. A. Kivelson, D. H. Lee, and S. C. Zhang, Phys. Rev. B **46**, 2223 (1992).
[6] H. W. Jiang, C. E. Johnson, K. L. Wang, and S. T. Hannahs, Phys. Rev. Lett. **71**, 1439 (1993).
[7] T. Wang, K. P. Clark, G. F. Spencer, A. M. Mack, and W. P. Kirk, Phys. Rev. Lett. **72**, 709 (1994).
[8] R. J. F. Hughes, J. T. Nicholls, J. E. F. Frost, E. H. Linfield, M. Pepper, C. J. B. Ford, D. A. Ritchie, G. A. C. Jones, E. Kogan, and M. Kaveh, J. Phys. Condens. Matter **6**, 4763 (1994).
[9] A. A. Shashkin, G. V. Kravchenko, and V. T. Dolgopolov, JETP Lett. **58**, 220 (1993).
[10] H. W. Jiang, C. E. Johnson, and K. L. Wang, Phys. Rev. B **46**, 12 830 (1992).
[11] See, for example, D. G. Polyakov and B. I. Shklovskii, Phys. Rev. Lett. **70**, 3796 (1993).
[12] V. J. Goldman, J. K. Jain, and M. Shayegan, Phys. Rev. Lett. **65**, 907 (1990).