Magnetic-Field-Induced Metal-Insulator Transition in Two Dimensions

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(Received 19 August 1993)

We carried out magnetotransport measurements and scaling analysis to report on a new magnetic-field-induced metal-insulator transition in two dimensions, where the separatrix between insulating and conducting states appears at a critical magnetic field. In the insulating state, a giant magnetoresistance is observed over a wide range of magnetic field. At the transition, the resistance remains nearly constant over two decades of temperature. In the conducting state a quantum Hall plateau is observed at $h/2e^2$. The critical exponent is in agreement with those of similar transitions in the quantum Hall regime, possibly reflecting a symmetry between the delocalization processes in 2D.

PACS numbers: 71.30.+h, 73.20.Fz, 73.20.Jc

The interplay between localization and the manifestation of macroscopic quantum phase coherence in two dimensions (2D) has been a subject of intense study. On the one hand, it is understood from the scaling theory of localization that all electronic states become localized by any small amount of disorder; thus no metallic phase with nonzero conductivity is allowed in 2D [1]. On the other hand, the electronic wave functions may become extended because of the particular quantum mechanical nature of a system, and there may be a vanishing resistance [2]. Of particular interest are the magnetic-field-induced 2D insulating-to-conducting transitions. At present the known ones include the superconductor-insulator transition [3], which is believed to reflect the fundamental nature between charge and flux duality in 2D [4], and the transitions between the plateaus in the quantum Hall effect [5], where the celebrated single-parameter scaling theory breaks down and must be replaced by a two-parameter scaling theory [6]. In this Letter we address questions that arise from the following consideration. Given that at zero magnetic field a system must be localized at sufficiently low temperatures, and that at strong magnetic fields the quantum Hall effect is present as an extended system, how does one regime cross over to the other? Does it occur at zero field or finite field? And does it proceed in a gradual manner or by a sharp transition? Theoretically these questions were first considered by Khmel'nitzkii and Laughlin, who argued that between localization and the quantum Hall effect there should be a sharp phase transition [7,8]. Here we present experimental evidence that there is indeed a sharp phase transition, where below a critical magnetic field the system exhibits insulating behavior while above the critical field the system exhibits conducting behavior, with the data collapsing onto the same scaling curve. The critical exponent was found to be consistent with the value found for the transitions between quantum Hall plateaus, hence reflecting a profound symmetry in the delocalization processes.

Our samples are modulation-doped GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructures. Because the experiments require a low-mobility, high-resistance, 2D electron gas, we use a special technique to create disorder in the samples. The heterostructures consist of a 1 μm thick GaAs buffer layer grown on a semi-insulating GaAs substrate, a 10 nm thick undoped $Al_{0.3}Ga_{0.7}As$ spacer, a 30 nm thick heavily Si-doped $Al_{0.3}Ga_{0.7}As$ layer, and a 50 nm thick Si-doped GaAs cap layer. The purpose of the heavy doping is to allow the positively charged Si ions to create a long-range random potential in the 2D electron gas. To prevent excess electrons from occupying the higher subbands, we deposit a 100–200 nm thick metal layer on top of lithographically patterned Hall bars (widths from 10 to 100 μm and lengths from 55 to 200 μm). This metal contact depletes electrons via the Schottky effect. The resulting sample is a very disordered 2D electron gas with a reduced carrier density. Specifically, without the metal contact a typical sample resistance, carrier density (n), and mobility at 4.2 K are 90 Ω, 8.8×10^{11} cm^{-2}, and 8×10^4 cm^2/V s, respectively; and with the metal contact these values become 10^4 Ω, 3×10^{11} cm^{-2}, and 2×10^3 cm^2/V s, respectively. The generality of our approach was demonstrated by varying the contact metals (Pb, Au, and Ti/Au) and finding qualitatively the same results. The dramatic increase in resistance with reduced carrier density is consistent with results from previous experiments using techniques of either directly gating a GaAs device [9] or partially removing the cap layer of the heterostructure using low energy ion milling to deplete the electrons [10]. These results were interpreted in terms of models concerned with the reduction in electron screening of the long-range random potential induced by the donor ions [11].

Measurements were taken in a rf-shielded room using either a ^{4}He cryostat or a ^{3}He+^{4}He dilution refrigerator. Low-pass filters were installed to minimize ground loop pickup. A PAR model 124A lock-in amplifier was operated at 3.2 Hz. A dc technique was also employed to check the results. Typically, excitation voltages at the lower temperatures were kept below 20 μV to minimize

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electron heating. As far as disorder is concerned, we emphasize that our samples were sufficiently disordered that there was no need to further deplete the carriers by a gate bias. Instead the top metal contact was left floating. This minimized complications from leakage currents as well as high electric-field-induced hopping events in the donor layer, which could result in a change in the defect configuration. A light-emitting diode (LED) was also installed to modulate the carrier density and therefore the sample resistance. The magnetic field was applied perpendicular to the sample.

Overall we have studied more than half a dozen samples with resistances ranging from a few kΩ to 20 kΩ. The zero-field behavior of these samples is consistent with previous weak localization studies in disordered metal films and in Si metal-oxide-semiconductor field-effect transistors [12,13]: At a few kΩ, the resistance follows both a logarithmic temperature ($\ln T$) dependence (at low voltage bias) and a logarithmic voltage ($\ln V$) dependence (at low temperature), and the resistance tends to saturate below 0.1 K. Around 10 kΩ the temperature dependence gradually changes from $\ln T$ to exponential hopping behavior. Here we present the data of two samples. Sample A had a resistance above 10 kΩ and was essentially in the hopping regime, while sample B had a resistance below 10 kΩ and was in the weakly localized regime. Figure 1 shows both the longitudinal sheet resistance (ρ_{xx}) and the Hall resistance (ρ_{xy}) of sample A as a function of magnetic field B. Here ρ_{xx} exhibits giant magnetoresistance, with a steep drop at small fields until B reaches 0.5 T, after which ρ_{xx} decreases linearly with increasing B. At higher fields, ρ_{xx} exhibits a shallow and a deep minimum, and a distinct quantum Hall plateau was observed at $h/2e^2$ in ρ_{xy}, corresponding to the filling factor 2. The transition from an insulating state to the quantum Hall liquid state appears to occur around 3 T.

We note that ρ_{xy} remains linear and temperature independent at low fields. Similar behavior has also been observed in high mobility samples in the insulating phases where the fractional quantum Hall effect series terminate [14,15]. Such insulating phases differ from conventional insulators in that as $T \rightarrow 0$, $\rho_{xy} = B/ne$ instead of going to infinity. It has been argued that this is a characteristic of a fundamentally new "Hall insulator" phase [16]. Whether the low field behavior in our disordered samples is relevant to this Hall insulator phase is not clear at this point.

Sample B was measured down to low temperatures (35 mK). Figure 2 shows the evolution of $\rho_{xx}(T)$ with increasing magnetic fields. The most remarkable feature of the data is that there appears to be a critical magnetic field (B_c) which separates the $\rho_{xx}(T)$ curves into two categories: Those below B_c appear to be insulating (ρ_{xx} increasing as $T \rightarrow 0$) and those above B_c appear to be conducting (ρ_{xx} decreasing as $T \rightarrow 0$). B_c is identified as the point where the resistance approaches a constant as $T \rightarrow 0$. Whether or not ρ_{xx} falls to zero immediately above B_c is not possible to resolve by the present measurements because the temperature may not be low enough. On the insulating side we observed that the resistance began to saturate below 100 mK, an effect that was observed previously [12,13]. This effect was attributed to electron heating, where the phonon relaxation time for the electrons becomes so long that the electrons cannot cool in the finite size of the sample [17]. Interestingly, Fig. 2 resembles the 2D superconductor-insulator transition observed in ultrathin homogeneous Bi films [18], where there is a critical thickness that separates all the superconducting curves from the insulating curves. In these systems there appears to be a direct transition from

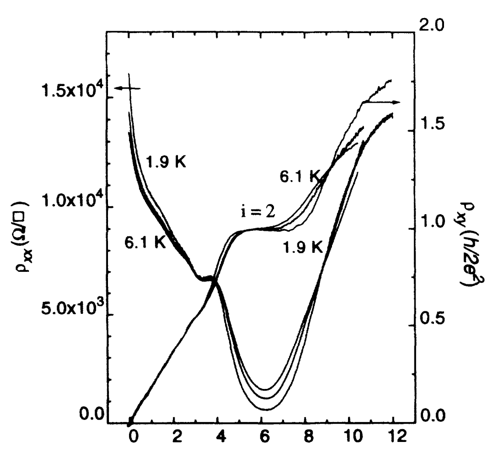

FIG. 1. Both ρ_{xx} (left axis) and ρ_{xy} (right axis) as a function of magnetic field B for sample A. Plotted are three temperatures: 6.1, 4.2, and 1.9 K.

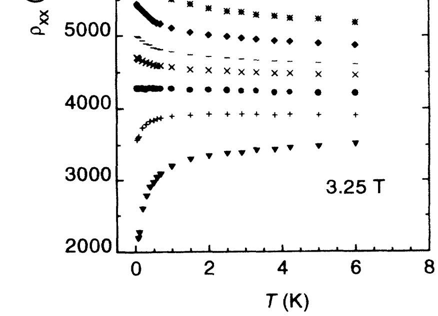

FIG. 2. Evolution of the temperature dependence of ρ_{xx} with magnetic field for the weak localization sample (B). From the highest curve to the lowest one, the magnetic fields are 0, 0.1, 0.5, 1.0, 1.5, 1.75, 2.15, 2.75, and 3.25 T. The critical magnetic field $B_c = 2.15$ T.

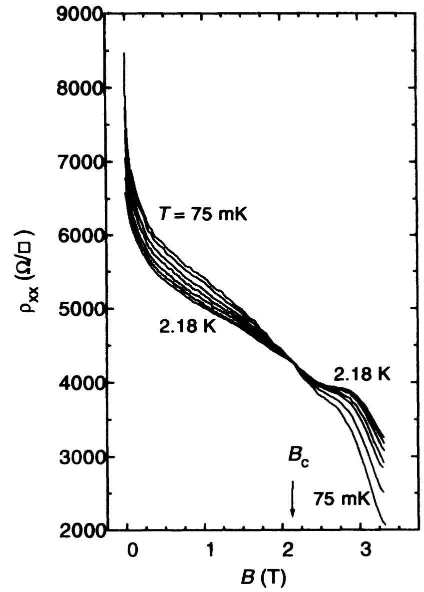

FIG. 3. The magnetoresistance curves $\rho_{xy}(B)$ for sample B. From the upper insulating curve to the lower insulating curve (i.e., $B < B_c$), the temperatures are 75 mK, 200 mK, 400 mK, 600 mK, 1.0 K, 1.5 K, and 2.18 K.

the insulating state to the superconducting state [19].

The isotherms of the ρ_{xx} vs B plots of Fig. 3 reveal more clearly the significance of B_c (indicated by the arrow). With decreasing temperature the crossover sharpens up, accompanied by a change of slope around B_c. In principle, as $T \to 0$ an infinitesimal increase of magnetic field can drive the system from the insulating state to the conducting state. Contrarily, exactly at $B_c = 2.15$ T, the resistance is nearly constant over more than two decades of temperature. It varies less than 0.5% from 6 to 1 K and less than 0.2% from 1 K down to 35 mK (limited by the instrument resolution). A constant critical resistance (ρ_c) has been argued to be a generic feature of all continuous insulating-to-conducting transitions in 2D as $T \to 0$ [20]. A system can either be insulating, perfectly conducting, or have a finite resistance. Furthermore, this critical resistance may be universal, depending only on its universality class. In our samples the critical resistance falls between 4 and 7 kΩ. Further examination of a universal critical resistance will require samples with a wider range of disorder and measurements down to lower temperatures than presently available.

In a 2D magnetic-field-induced phase transition the characteristic length scale ξ diverges as $|B-B_c|^{-\nu}$ and the characteristic frequency Ω vanishes as $\xi^{-z} = |B-B_c|^{\nu z}$, where ν and z are two dynamical exponents. The data near the transition should satisfy the scaling function [21]

$$\rho_{xx}(B,T) = \rho_0 \tilde{\rho}[c_0 |B-B_c|/T^{1/\nu z}], \qquad (1)$$

where $|B-B_c|/T^{1/\nu z}$ is a dimensionless scaling variable. A direct experimental determination of the critical exponent $\kappa = 1/\nu z$ can then be made by evaluating $|d\rho_{xx}/dB|_{B_c}$ at fixed T, i.e.,

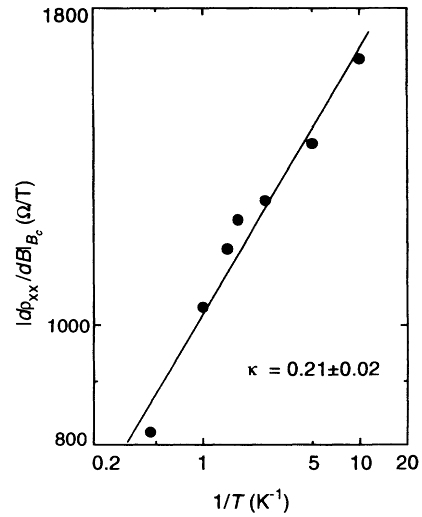

FIG. 4. $|d\rho_{xx}/dB|_{B_c}$ vs $1/T$ plotted on a logarithmic scale. The slope of the solid line is the critical exponent κ, as indicated in the figure.

$$|d\rho_{xx}/dB|_{B_c} = \rho_0 c_0 T^{-\kappa} \tilde{\rho}'(0) \qquad (2)$$

and plotting $|d\rho_{xx}/dB|_{B_c}$ vs T^{-1} on a logarithmic scale. The results are shown in Fig. 4. The solid line is consistent with Eq. (2) and from the slope we deduce $\kappa = 0.21 \pm 0.02$. It is interesting to compare this result with previously known values of κ for the transitions between adjacent Hall plateaus in the integer quantum Hall effect. For those transitions between non-spin-split Landau levels, κ was found to be 0.21 ± 0.02 in both InGaAs/InP samples [22,23] and AlGaAs/GaAs samples [24]. More recently in microwave frequency measurements in AlGaAs/GaAs samples, κ was found to be 0.20 ± 0.05, with $z=1$ and $\nu = 14/3$ [25]. The non-spin-split states are due to the disorder, as is the case in our samples. The agreement between our experiment and these experiments suggests that such delocalization transitions belong to the same universality class. We note that for spin-split Landau levels in the integer quantum Hall effect κ is almost twice as large (close to 0.42). This difference can be attributed to different delocalization processes, where the spin-split and the non-spin-split transitions may belong to two different universality classes [5,22–25].

Once B_c and κ are known, the scaling form $\tilde{\rho}$ can then be independently tested without the use of any fitting parameters. This is shown in Fig. 5, where $\rho_{xx}(B,T)$ is plotted against the absolute value of the scaling variable, $|B-B_c|/T^{\kappa}$. The two branches $B < B_c$ and $B > B_c$ are identified as above and below the transition. Good scaling is observed over three decades of $|B-B_c|/T^{\kappa}$. The scaling is also sensitive to the choice of B_c. A 5% variation in B_c produces noticeable deviation in the data. These results strongly suggest that we have indeed observed a genuine phase transition from localization to the

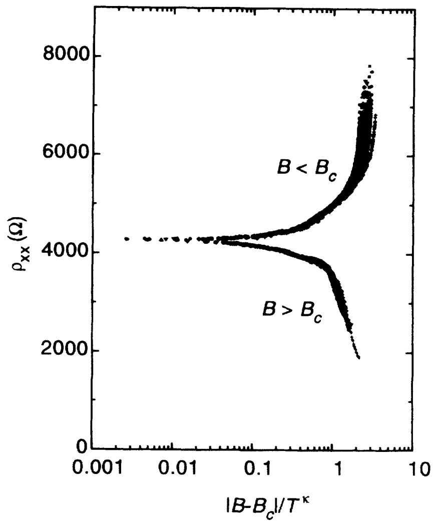

FIG. 5. Scaling analysis with ρ_{xx} against the dimensionless scaling variable $|B-B_c|/T^\kappa$. The two branches $B<B_c$ and $B>B_c$ are indicated as above and below the transition.

delocalization. This also agrees with the theoretical predictions of a sharp delocalization phase transition by Khmel'nitzkii and Laughlin [7,8].

Recent theoretical work on the global phase diagram of the quantum Hall effect suggested that in a disordered 2D system there is a direct transition from an insulating state to the quantum Hall liquid state with increasing magnetic field [16]. One then observes a series of transitions between Hall plateaus and at even higher fields the system becomes a Hall insulator. Our results are consistent with this picture and reflect the symmetry between delocalization processes at low and high fields, except that the predicted transition occurs at the lowest Landau level while in our experiments B_c is below the filling factor 4. The reason may be that in the low-field regime where the elastic scattering length is comparable to the cyclotron radius, the theory may be further constrained. In such instances the crossing of Landau levels must be considered.

In summary, studies of magnetotransport properties in weak localization and variable-range-hopping regimes have revealed a new magnetic-field-induced metal-insulator transition. The critical exponent of the transition was determined and good scaling behavior was observed. The existence of this phenomenon implies that the transition from the localization regime to the quantum Hall effect regime is a genuine phase transition.

The authors gratefully acknowledge Professor A. M. Goldman, Professor C.-R. Hu, Professor N. E. Israeloff, Professor D. E. Khmel'nitzkii, Professor D.-H. Lee, Professor Q. Niu, and Professor V. Pokrovsky for helpful discussions. We also thank Dr. Y.-C. Kao for providing some of the MBE material. This work was supported in part by the Texas Advanced Research Program, Grant No. 999903-136, and by NSF Grant No. DMR9107460.

Note added.—Independently, H. W. Jiang and co-workers [26] recently reported similar delocalization phenomena in samples more disordered than ours.

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