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Effect of long-range potential fluctuations on scaling in the integer quantum Hall effect

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We report a set of transport data taken in two low-mobility GaAs/$Al_xGa_{1-x}As$ heterostructures. When $T > 200$ mK, we find that the T dependence of $(d\rho_{xy}/dB)^{max}$ behaves differently in different Landau levels, whereas when $T < 200$ mK, it behaves like $T^{-0.42}$ as reported by Wei *et al.* [Phys. Rev. Lett. **61**, 1294 (1988)]. The characteristic $T(=200$ mK) for observing the critical behavior is much lower than that of previous observations in the $In_xGa_{1-x}As$/InP heterostructure. This lowering of T for scaling is attributed to the dominance of long-range potential fluctuations due to the remote ionized impurities in the $Al_xGa_{1-x}As$.

The appearance of the integer quantum Hall effect (IQHE) in a two-dimensional electron gas (2DEG) in high magnetic fields (B) at low temperatures (T) indicates that the electronic states are localized except at some singular energies, where they are delocalized.[1] The transition of the electronic states at the Fermi level (E_F) from localized to delocalized states, when B is swept through adjacent quantum Hall plateaus, has been found to exhibit scaling behavior.[2,3] In particular, in an $In_xGa_{1-x}As$/InP heterostructure, the T dependence of the peak of the derivative of the Hall resistance ρ_{xy} with respect to B [$(d\rho_{xy}/dB)^{max}$] diverges like $T^{-\kappa}$ ($\kappa=0.42$), independent of Landau levels, when $T < 4.2$ K. This result is a direct consequence of the scaling theory of Pruisken.[4] Basically, the scaling behavior is due to the quantum interference of electrons in a disordered medium. At finite T, the inelastic scattering length (l_{in}) is the largest length scale within which the quantum interference makes sense, and therefore is the effective sample size.[5] The scaling theory of the IQHE (Refs. 6 and 7) assumes the existence of uncorrelated, δ-function-like potential fluctuations. This is realized in $In_xGa_{1-x}As$/InP heterostructures where the correlation length of the random potential is approximately equal to the lattice constant. In this paper, we discuss the situation in GaAs/$Al_xGa_{1-x}As$ heterostructures in which the potential fluctuations are long range.

In the GaAs/$Al_xGa_{1-x}As$ samples that we have studied[8] (all grown by molecular-beam epitaxy), we find that in most cases, the T-dependent behavior of $(d\rho_{xy}/dB)^{max}$ is sample and Landau-level dependent. A similar result is also reported in a recent paper by Koch *et al.*[9] On the other hand, in two of our samples, we did find evidence that the $T^{-0.42}$ critical behavior is observed for $T < 200$ mK. The first sample has an electron density $n=1.9\times10^{11}$ cm^{-2} and a mobility $\mu=55\,000$ cm^2/V s at 4.2 K. Figure 1 shows the transport coefficients ρ_{xx} and ρ_{xy} at 66 mK. There is no signature of the fractional quantum Hall effect that is observed in samples with higher mobility,[10] thus the many-body effect is not relevant in this sample. The other sample has $n=2.1\times10^{11}$ cm^{-2} and $\mu=65\,000$ cm^2/V s at 4.2 K. We find that the transport properties in these two samples are the same in all respects. Therefore, we will present the data from the first sample only.

In Fig. 2 we plot the T dependent $(d\rho_{xy}/dB)^{max}$ for 30 mK $< T <$ 4.2 K in three Landau levels. There are four different symbols in each curve representing data taken from four different runs. We notice that for $T > 200$ mK, $(d\rho_{xy}/dB)^{max}$ behave differently in each Landau level. However, they behave more or less the same for $T < 200$ mK. The straight line on top of this figure is drawn for reference purpose. It has a slope of 0.42 on this log-log plot. The data suggest that for $T < \sim 200$ mK, $(d\rho_{xy}/dB)^{max}$ has a power-law dependence, $T^{-\kappa}$, independent of Landau levels. The exponent $\kappa=0.42$, the same as that reported previously in the $In_xGa_{1-x}As$/InP sample.[2]

The main difference from the previous $In_xGa_{1-x}As$/InP results is the value of T_{sc}, which is the T where the $T^{-0.42}$ power-law behavior starts to appear ($T_{sc}\sim200$ mK in the present sample and ~4 K in the $In_xGa_{1-x}As$/InP sample of Ref. 2). We find that T_{sc} in the GaAs/$Al_xGa_{1-x}As$ sample is substantially lower than T, where the conductivity peak (σ_{xx}^{max}) has a maximum (see Fig. 3) and which equals about 1 K. We emphasize that the latter T is solely an effect of the thermal width of the Fermi-Dirac distribution,[2,3] and in $In_xGa_{1-x}As$/InP it equals T_{sc}. Experimentally, transport coefficients are obtained by measuring a voltage across two contacts which are typically a millimeter apart. This procedure is viewed as an average over the macroscopic sample composed of a large number of microscopic effective samples, each with a size of l_{in}. The observation of much lower T_{sc} in the GaAs/$Al_xGa_{1-x}As$ sample is an indication of the presence of long-range potential fluctuations. More specifically, the lack of the power-law behavior in the range of T from 1 K to 200 mK is mainly a result of l_{in} not being much larger than the distance over which the potential fluctuations are correlated.

The qualitative difference in the potential distributions in the $In_xGa_{1-x}As$/InP and the GaAs/$Al_xGa_{1-x}As$ heterostructures is also obvious from the metallurgy of the

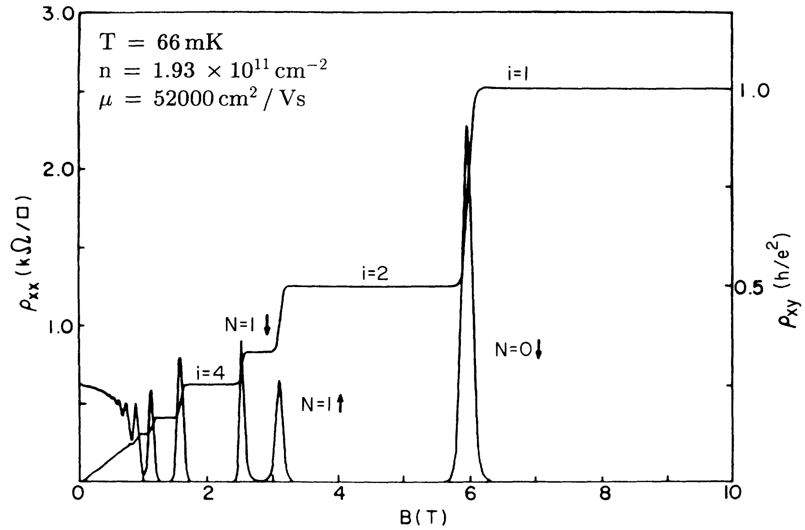

FIG. 1. Magneto-transport coefficients ρ_{xx} and ρ_{xy} vs B at $T=66$ mK in a GaAs/Al$_x$Ga$_{1-x}$As heterostructure. $N=1\downarrow$, $1\uparrow$, and $0\downarrow$ are the indexes for spin ($\downarrow,\uparrow$) split Landau levels, in which the E_F resides when B is swept through adjacent quantum Hall plateaus.

sample. Since the 2DEG in the In$_x$Ga$_{1-x}$As/InP heterostructure is in the In$_x$Ga$_{1-x}$As layer, which is an alloy,[11] the potential fluctuations are therefore short ranged compared to the cyclotron radius (typically 100 Å) and hence to $l_{\rm in}$. On the other hand, the 2DEG in the GaAs/Al$_x$Ga$_{1-x}$As heterostructures is in the GaAs layer, and it is well known that the dominant scattering mechanism at low T is the remote ionized impurities away from the 2DEG layer.[12,13] One should then expect smooth, long-range potential fluctuations.[14] The dominance of long-range potential fluctuations lowers the T, below which scaling starts and complicates the observability of the critical phenomenon. Given the T available to the experiment, our data is quite limited compared to that of our previous work on In$_x$Ga$_{1-x}$As/InP, in which case the critical behavior in $d\rho_{xy}/dB$, $(\Delta B)^{-1}$, $d^2\rho_{xx}/dB^2$, and $d^3\rho_{xy}/dB^3$ are well established in more than two decades in T.[3]

Another striking difference may be found in the spin ($\downarrow,\uparrow$) dependence of $\sigma_{xx}^{\max}$ corresponding to the $N=1\uparrow$ and $1\downarrow$ Landau levels for T less than $\sim$1 K in Fig. 3. They are not equal as in the case of the In$_x$Ga$_{1-x}$As/InP sample. Although there is a clear tendency toward the $T^{-0.42}$ critical behavior in $(d\rho_{xy}/dB)^{\max}$ at low T, the ori-

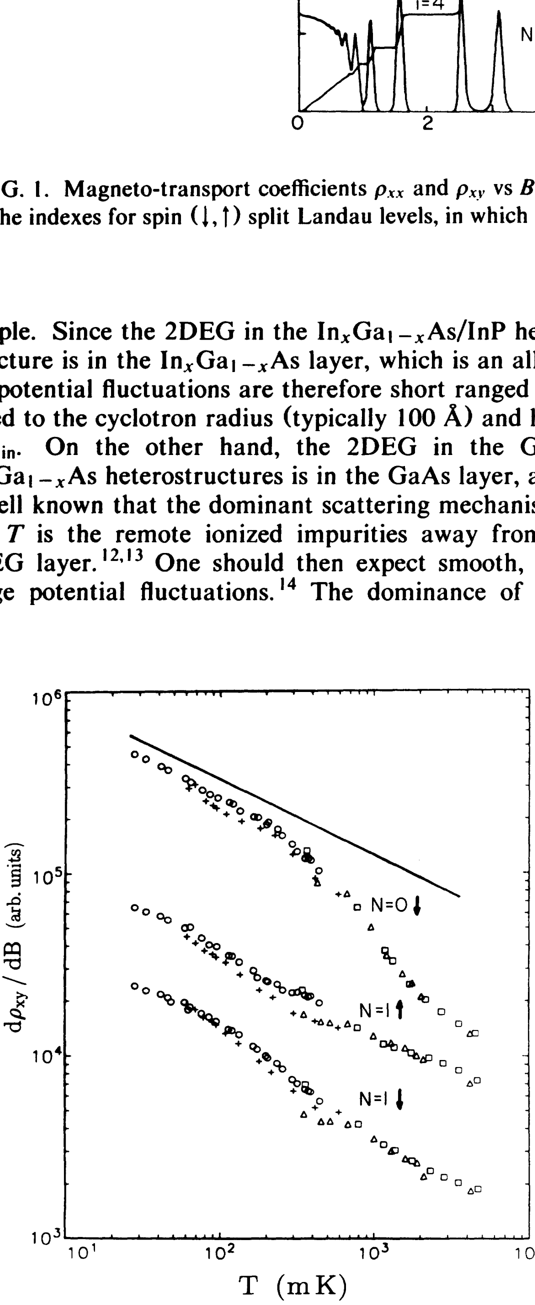

FIG. 2. T dependence of $(d\rho_{xy}/dB)^{\max}$ for three Landau levels, $N=1\downarrow$, $1\uparrow$, and $0\downarrow$. The solid line is drawn for reference purpose and has a slope of 0.42.

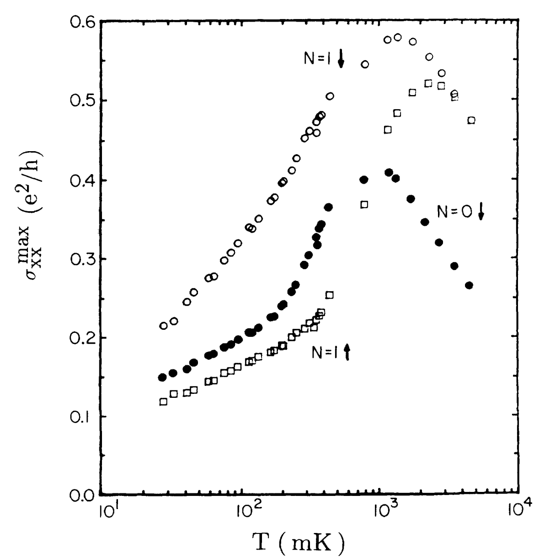

FIG. 3. $\sigma_{xx}^{\max}$ as a function of T for three Landau levels, $N=1\downarrow$, $1\uparrow$, and $0\downarrow$.

gin of this effect, not relevant to scaling, is not understood at present.

In summary, we may say that the critical behavior in the metal-insulator transition in the IQHE is severely affected by the long-range nature of the potential fluctuations in the GaAs/$Al_xGa_{1-x}As$ samples, in contrast to the short-range random alloy potential in the $In_xGa_{1-x}As$/InP samples. The dominance of long-range potential fluctuations lowers the T below which the scaling becomes observable. In two of our samples, scaling and the related critical behavior are observed for T less than 200 mK. We conclude from this observation that the apparent lack of scaling in most of our GaAs/$Al_xGa_{1-x}As$ samples is due to crossover effects, which are dependent on the microscopic details of the sample, and much lower T will be needed to observe scaling in these samples.

Note added. While this paper was being reviewed, we became aware of the recent work by Koch *et al.* [Phys. Rev. Lett. **67**, 833 (1991)], who found that the temperature exponent p for the inelastic scattering length $l_{in}(=T^{-p/2})$ depends on the quality of samples. Thus, they concluded that $\kappa(\sim p)$ is material dependent in the T range available in the laboratory. On the other hand, if l_{in} is due to electron-electron interaction at low T, it is likely that p should not depend on the details of disorder in the limit of very large sample size.

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