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# Experimental Evidence for Weak Insulator-Quantum Hall Transitions in GaN/AlGaN Two-Dimensional Electron Systems

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We report comparative magnetoresistance measurements of the two-dimensional electron gas formed in two different GaN/AlGaN quantum well structures with different starting disorder. The longitudinal magnetoresistance measurements for both the samples exhibited temperature-independent crossing points, evidence for a weak insulator - quantum Hall transition. Our data suggest that the onset of Landau quantization does not correspond to the crossing point. Moreover, the effect of the electron-electron interaction must be taken into account because the Hall resistivity shows a strong temperature dependence in the more disordered sample. Our experimental results, therefore, urge further studies on the low-field weak insulator - quantum Hall transition.

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## I. INTRODUCTION

Recently significant progress has been made in developing III-V nitride materials. As a result, heterostructures based on nitrides such as AlGaN, GaN, InGaN, and InN have been studied extensively [1–9]. In particular, AlGaN/GaN heterostructures have been attracting much interest for their potential applications in electronic and optical devices such as high-frequency and high-power electrical devices, laser diodes and ultraviolet detectors. It is worth mentioning that in an AlGaN/GaN heterojunction spontaneous polarization exists due to the positions of the anion and the cation in the lattice, and piezoelectric polarization exists due to the strain in the heterostructure. These two features can be exploited in making a high electron mobility transistor (HEMT) [4–7] with an extremely high density ($\sim10^{13}$ cm$^{-2}$) two-dimensional electron gas (2DEG) present near the AlGaN/GaN interface without intentional doping.

There has been much interest in magnetic field induced transitions in the integer quantum Hall effect [10]. Experimental evidence for the magnetic field induced transition from an Anderson insulator to a quantum Hall conductor has already been reported [11]. According to scaling theory of localization, [12] in zero magnetic field, all electronic states are localized at low temperatures. In order to account for the evolution of electronic state from being extended in a strong magnetic field to being localized at zero magnetic field ($B = 0$ T), Laughlin [13]

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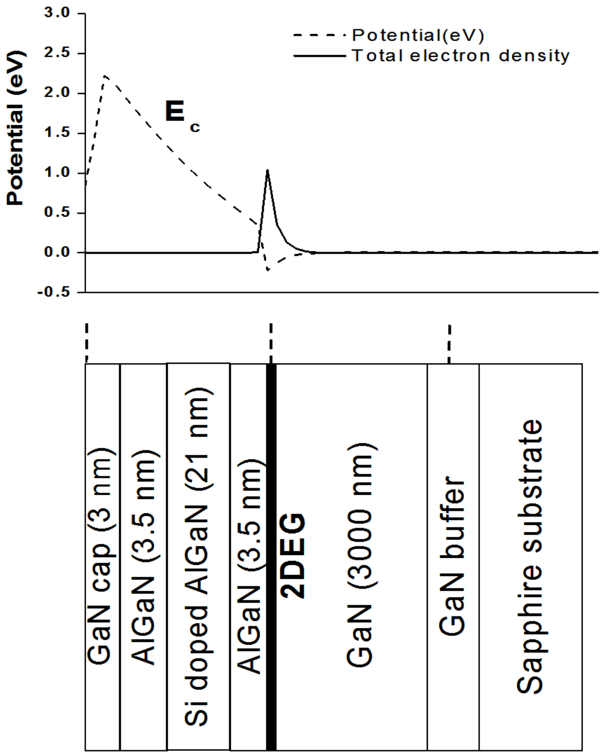

Fig. 1. Conduction band diagram and sample structure for sample A.

suggested that the extended state would float up in energy as the magnetic field was reduced. Thus, for a given electron density and sufficiently low magnetic field, all extended states would be above the Fermi energy ($E_F$) and the system become insulating. This scenario is crucial to the global phase diagram for the quantum Hall effect proposed by Kivelson *et al.* [14]. As the magnetic field is increased, extended states sink in energy and fall below the Fermi energy. When the Fermi level is in the extended state, the system attains a quantum Hall liquid state with $\rho_{xx} \to 0$ and $\rho_{xy} \to h/(\nu e^2)$.

Although magnetic-field-induced transitions, which can be described with the global phase diagram, are now well studied, it is still an unsettled issue whether the observed direct transition from an insulator to a high Landau level filling factor ($\nu > 2$) at low magnetic fields is a genuine phase transition [10,15–17]. Huckestein argued that this transition is not a phase transition, but a cross over due to a weak localization and the strong reduction in conductivity when Landau quantization becomes dominant. At this "crossover", $\rho_{xx} \sim \rho_{xy}$. At the crossing point, the value of $\omega_c\tau$ (or $\mu B$) is found to be approximately 1. This crossing point separates two regions with different temperature behaviors: At low fields, the longitudinal resistivity ($\rho_{xx}$) increases slowly with decreasing temperature, and at high fields $\rho_{xx}$ increases with increasing temperature. However, recently, it has been shown that a crossover from localization to Landau quantization can cover a wide range of magnetic fields [17,18], in sharp contrast to the argument raised by Huckestein. Moreover, experimental data in the vicinity of the crossing point show good scaling behavior, suggesting that the low-field weak insulator - quantum Hall liquid transition is a genuine quantum phase transition.

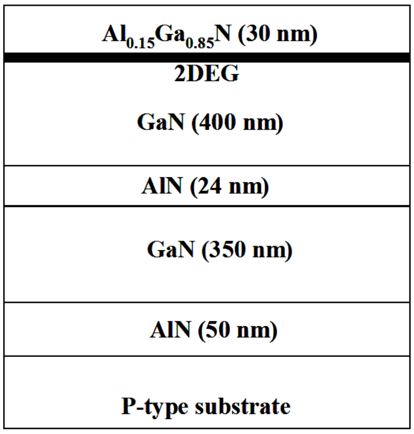

Fig. 2. Sample structure for sample B.

In this paper, we report an experimental study of weak insulator - quantum Hall transitions in two different 2DEGs in GaN/AlGaN heterostructures. We benefit from the fact that one of these samples (Sample A) has been studied before [9]. We found that in both 2D systems, $\rho_{xx} \sim \rho_{xy}$ near the T-independent point in $\rho_{xx}$. For Sample A, at the crossing point, the product $\mu B$ is close to 1, where the mobility $\mu$ is determined from the zero-field resistivity and the carrier density at the lowest measurement temperature. On the other hand, for Sample B, although $\rho_{xx} \sim \rho_{xy}$ near the T-independent point in $\rho_{xx}$, at the crossing point, the product $\mu B$ is $\sim$ 0.6, considerably smaller than 1. A possible reason for this is that the mobility has to be determined from the resistivity near the crossing point. In this case, $\mu B$ is indeed close to 1. Our data suggest that the onset of Landau quantization does not correspond to the crossing point. Moreover, the effect of electron-electron interactions must be taken into account because the Hall resistivity shows a strong T dependence in the more disordered sample. Our experimental results urge further studies on the area of the low-field weak insulator - quantum Hall transition.

## II. EXPERIMENT

Two samples are used in this work. Sample A is a modulation doped GaN/AlGaN heterostructure grown on a sapphire substrate and has been studied before [9]. Sample B is a nominally undoped GaN/AlGaN heterostructure grown on Si [19]. The structures of the two samples are shown in Figs. 1 and 2. It is worth pointing out that Sample B is compatible with complimentary metal-oxide

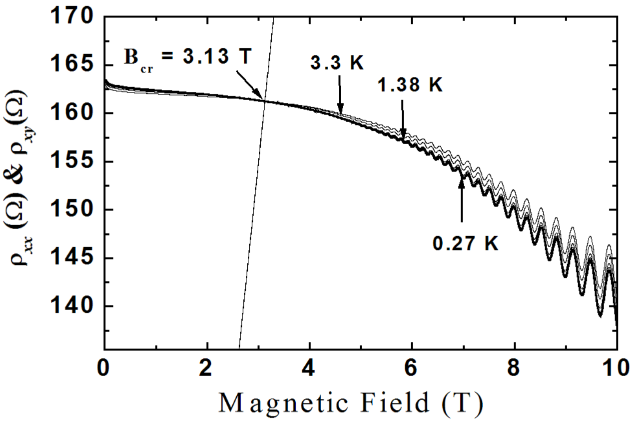

Fig. 3. Longitudinal resistivity as a function of the magnetic field at 0.27 K, 1.38 K and 3.3 K for sample A.

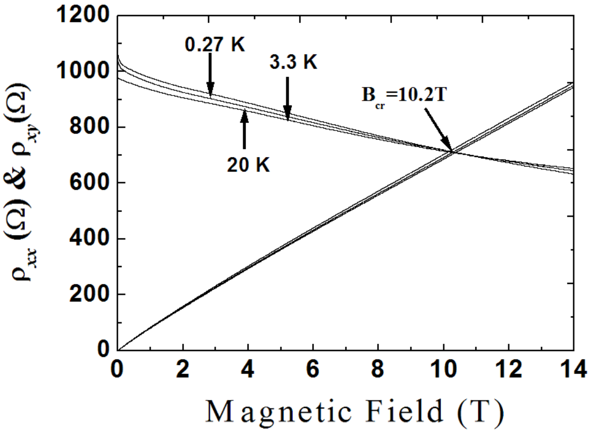

Fig. 4. Longitudinal resistivity as a function of the magnetic field at 0.27 K, 3.3 K and 20 K for sample B.

semi-conductor technology and thus, has a great potential for device applications. Measurements have been performed by using a four-terminal method using standard ac phase-sensitive lock - in techniques and a current of 100 nA.

## III. RESULTS AND DISCUSSION

Fig. 3 shows the observed magnetoresistance for various values of the magnetic field for sample A at temperatures of 0.27 K, 1.38 K and 3.3 K. At weak magnetic fields, there is a sharp decrease in the longitudinal resistivity due to suppression of the weak localization effect. As the magnetic field is increased, $\rho_{xx}$ exhibits a temperature independent crossing point at a magnetic field of 3.13 T. With further increases in the magnetic field, sample A exhibits a SdH oscillation with the SdH minimum decreasing with decreasing temperature.

Fig. 4 presents the result of the magnetoresistance study carried out for sample B at temperatures of 0.27 K, 3.3 K and 20 K. This sample also exhibits negative magnetoresistance near zero fields due to suppression of the weak localization effect, but it is to be noted that a temperature independent crossing point occurs at a high magnetic field around 10.2 T. This crossing point separates two regions with different temperature dependences. At fields below 10.2 T, the system shows an insulating behavior, and above 10.2 T it exhibits a quantum-Hall-liquid behavior with a longitudinal resistivity decreasing with decreasing temperature. Moreover, even at high magnetic field this sample does not show any SdH oscillation which is an indication that sample B has a large carrier density and that the Landau levels are broadened to a great extent due to disorder.

As Fig. 4 shows, the Hall resistivity appears to decrease with increasing temperature. One might argue that the carrier density varies with increasing temperature. In a nominally the same AlGaN/GaN heterostructure that had been SiN treated during crystal growth [20], we are able to observe SdH oscillations in the high field region. In this sample, we note that the carrier density determined from SdH oscillations remains constant over a wide range of measurement temperatures [20]. Since these two samples are almost identical, the electron density is expected to remain the same in both samples. Therefore, the observed change in the Hall slope observed in Sample B must be due to electron-electron interaction effects [21].

We found that in both 2D systems, $\rho_{xx} \sim \rho_{xy}$ near the T-independent point in $\rho_{xx}$. For Sample A, at the crossing point the product $\mu B$ is close to 1, where the mobility $\mu$ is determined from the zero-field resistivity and the carrier density at the lowest measurement temperature. On the other hand, for Sample B, although $\rho_{xx} \sim \rho_{xy}$ near the T-independent point in $\rho_{xx}$, at the crossing point, the product $\mu B$ is $\sim 0.6$, considerably smaller than 1. A possible reason for this is that the mobility has to be determined from the temperature dependence of the mobility [22]. If we take the resistivity near the crossing point, $\mu B$ is indeed close to 1.

We can see that in both Samples, near the crossing point, there is no signature of Landau quantization, *i.e.* no SdH oscillations. In particular, there are no SdH oscillations at all in Sample B. Therefore, our data clearly suggest that the crossing point does not correspond to the onset of Landau quantization.

## IV. CONCLUSIONS

We have reported experimental evidence for insulator - quantum Hall transitions observed in two samples with different disorder. The longitudinal magnetoresistance measurements exhibited temperature- independent crossing points for both the samples. In particular, in the more-disordered sample, no SdH oscillations were observed over the whole measurement range. Moreover, the effect of electron-electron interactions must be taken into account because the Hall resistivity shows strong temperature dependence. Our experimental results suggest that further studies are required in order to obtain a thorough understanding of the low-field weak insulator - quantum Hall transition.

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