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Experimental Evidence for Drude-Boltzmann-Like Transport in a Two-Dimensional Electron Gas in an AlGaN/GaN Heterostructure

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AlGaN/GaN heterostructures have been attracting a great deal of interest because of their great potential applications as light-emitting-diodes, high-electron-mobility transistors (HEMTs), and detectors operating in the visible-to-ultraviolet range. The performances of these devices are governed by the electronic properties of the two-dimensional electron gas (2DEG) formed at the interface of AlGaN/GaN heterostructure. In this work, we report transport measurements for an AlGaN/GaN 2DEG as functions of the magnetic field B over a wide range of temperature (4.682 K $\leq T \leq$ 80 K). At the highest measurement temperature of 80 K, the longitudinal resistance is nominally B-independent, compelling experimental evidence for Drude-Boltzmann-like transport in a 2D system.

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I. INTRODUCTION

Recently, efforts in developing III-V nitride family have led to significant progress in improving the material quality. Heterostructures based on these nitride materials are, therefore, being studied intensively [1–12]. In particular, AlGaN/GaN heterostructures have been attracting a great deal of both theoretical and experimental interest because of their applications in high-power microwave devices, in high-frequency field-effect transistors, in blue light-emitting-diodes, and in high-electron-mobility transistors (HEMTs) [13–19]. It is worth mentioning that in addition to proving semiconductors can have large band gaps, the nitride materials have two very interesting features. The first is a spontaneous polarization present in the nitride structures as a result of the anion and cation positions in the lattice. In heterostructures, the difference between the spontaneous polarizations of the two layers can be used to create a high electron density. The second is the piezoelectric polarization for a nitride heterostructure with strain. Effective built-in internal fields can be produced near the AlGaN/GaN interface. These two effects have been exploited to design nominally undoped AlGaN/GaN HEMTs with extremely high sheet electron concentrations. The performances of GaN-based optoelectronic devices, such as light-emitting diodes and HEMTs, are governed by the electronic properties of the two-dimensional electron gas (2DEG) formed in the AlGaN/GaN quantum well. Therefore, it is highly desirable to obtain a thorough understanding of the underlying physics of transport in an AlGaN/GaN 2DEG in order to optimize GaN-based device's performance.

At low temperatures, the conductivity of a degenerate two-dimensional electron gas is governed by quan-

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tum corrections to the Drude conductivity, σ_D. Except for Shubnikov-de Haas oscillations in a high magnetic field, there are still two principal corrections: the weak localization (WL) in a very weak magnetic field and the electron-electron (e-e) interaction in an intermediate field [20]. A general formula for the longitudinal conductivity in a magnetic field can be written as follows:

$$\sigma_{xx} = \sigma_D + \Delta\sigma_{xx}^{ee}(T) + \Delta\sigma_{xx}^{WL}(B), \tag{1}$$

where σ_D is a constant term due to Drude-Boltzmann transport, $\Delta\sigma_{xx}^{ee}(T)$ is a function of the temperature (T), $\Delta\sigma_{xx}^{WL}$ is a function of the magnetic field (B).

Weak localization is the quantum interference of the conducting electrons with the defects of the system, and this theory predicts a correction to the magnetoconductivity, $\Delta\sigma_{xx}^{WL}(B)$, given by [21,22]

$$\Delta\sigma_{xx}^{WL}(B) = \sigma_{00}\left[\psi\left(\frac{1}{2}+\frac{\hbar}{4eDB\tau_i}\right) - \psi\left(\frac{1}{2}+\frac{\hbar}{4eDB\tau_e}\right) + \ln\left(\frac{\tau_i}{\tau_e}\right)\right], \tag{2}$$

where τ_e and τ_i are the elastic and the inelastic scattering times, respectively, ψ is the digamma function, and D is the electronic diffusion constant given by $D = v_F^2\tau_e/2$. The application of a magnetic field influences this interference due to the Aharonov-Bohm effect [23]. The theory of the weak localization effect deals with noninteracting electrons and such phenomena arise from the single-particle quantum interference effect. In a very weak magnetic field, it causes a rapid increment of the magnetoconductivity as we increase the magnetic field.

The Coulomb interactions between conduction electrons also give rise to a quantum correction term to the classical Drude conductivity. The term $\Delta\sigma_{xx}^{ee}(T)$, which is B-independent, should only result in a vertical shift of this contribution. Until recently, our understanding of the e-e interaction corrections to the conductivity of a 2DEG was based on the seemingly unrelated theories developed for two opposite regions: the diffusive region [24] $k_BT\tau/\hbar << 1$, and the ballistic region $k_BT\tau/\hbar >> 1$. Physically, the diffusive condition implies that the effective interaction time, $\hbar/k_BT$, is larger than the momentum relaxation time τ, therefore, two interacting electrons experience are scattered by many impurities whereas in the ballistic region, electrons interact when scattered by a single impurity. In 2001, Zala, Narozhny, and Aleiner (ZNA) developed a new theory of a electron-electron interaction correction to the conductivity [25,26] that bridged the gap between the two theories known previously [24,27] One of the important conclusions of this theory is that the interaction corrections to the conductivity in both regions have a common origin: the coherent scattering of electrons by Friedel oscillations. This can also be reformulated in terms of returns, diffusive and ballistic, of an electron to a spatial region that it has already visited.

In the diffusive limit, one finds [24,28,29] for the logarithmically divergent correction to the diagonal conductivity, $\Delta\sigma_{xx}^{ee}$,

$$\Delta\sigma_{xx}^{ee} = \frac{e^2}{2\pi^2\hbar}\ln\left(\frac{k_BT\tau}{\hbar}\right) \times\left[1+3\left(1-\frac{\ln(1+F_0^\sigma)}{F_0^\sigma}\right)\right] \tag{3}$$

where F_0^σ is the interaction constant in the triplet channel and depends on the interaction length. The theory predicts a logarithmic temperature dependence of the longitudinal conductivity. It is clear, that the sign of this logarithmically divergent correction may be positive (metallic) or negative (insulating), depending on the value of F_0^σ. The interaction correction gives rise to a parabolic negative magnetoresistance (NMR) that can be expressed by the following relation at $\omega_c\tau > 1$ [30]:

$$\rho_{xx} = \frac{1}{\sigma_0} + \frac{1}{\sigma_0^2}\left(\mu^2B^2\right)\Delta\sigma_{xx}^{ee}(T), \tag{4}$$

where μ is the electron mobility. This relation is derived by converting the conductivity tensor into the resistivity tensor and by using the facts that in the diffusive region, the Hall conductivity is not affected by interactions, $\Delta\sigma_{xy}^{ee} = 0$, and that $\Delta\sigma_{xx}^{ee}(T)$ and $\Delta\sigma_{xx}^{ee}(T)$ do not change when a strong magnetic field is applied [31]. In our experiment, we also observe the parabolic negative behavior for our $\rho_{xx}(B)$ at the lowest temperature (4.682 K). On the other hand, in the ballistic region [27,32] the interaction correction is given by:

$$\Delta\sigma_{xx}^{ee} = -\frac{e^2}{\pi\hbar}\left(\frac{k_BT\tau}{\hbar}\right)f(r_s), \tag{5}$$

where $f(r_s)$ is a positive function of the gas parameter of the system, r_s. Therefore, in this region, the temperature dependence of these parameters becomes linear.

It is well-known that the Drude-Boltzmann model is equivalent to a stochastic redistribution of all scattering centers after each collision predicts zero magnetoresistance (MR). That is, the longitudinal resistance of a sample is magnetic-field (B) independent. Therefore, the Shubnikov-de Haas oscillations periodic in $1/B$ can be regarded as deviations from Drude-Boltzmann transport because the applied magnetic field is so large and cannot be considered as a perturbation to the 2D Fermi circle. It is known that a two-dimensional GaN electron gas can exhibit negative MR [7] due to electron-electron interactions [33]. Classical percolation of electrons in a random array of strong scatterers on the background of a smooth impurity potential can also give rise to a negative MR in a 2D system. The simplest case of Drude-Boltzmann-like transport appears to be elusive in a real 2D system as there are so many mechanisms that can give rise to a nontrivial MR [34]. In this article, we report magnetotransport measurements on an AlGaN/GaN two-dimensional electron gas over a wide range of temperature (4.682 K

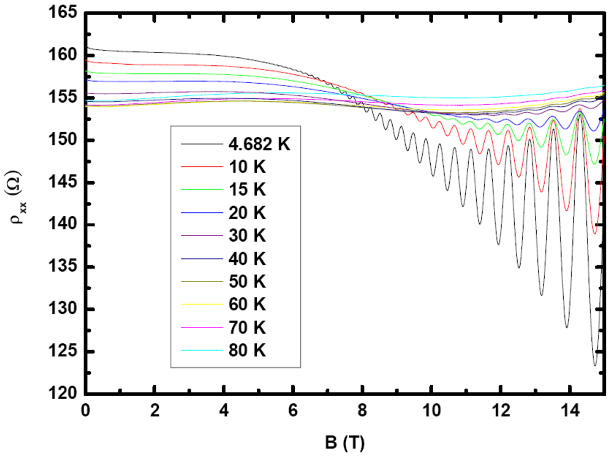

Fig. 1. Longitudinal magnetoresistivity as a function of the magnetic field, $\rho_{xx}(B)$, over a wide range of temperatures (4.682 K $\leq T \leq$ 80 K).

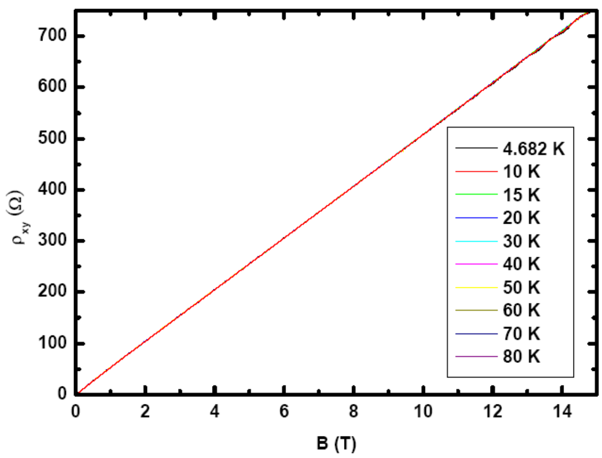

Fig. 2. Hall magnetoresistivity as a function of the magnetic field, $\rho_{xy}(B)$, over a wide range of temperatures (4.682 K $\leq T \leq$ 80 K).

$\leq T \leq$ 80 K). In the low-temperature region, the magnetoresistivity oscillate as the magnetic field increases. At the highest measurement temperature of $T = 80$ K, *i.e.*, in the quasiclassical region, the longitudinal resistance is nominally magnetic-field independent, which is evidence for Drude-Boltzmann-like transport in a 2D electron system.

II. EXPERIMENT

The sample that we studied is an Metal-organic-chemical-vapor-deposition(MOCVD)-grown AlGaN/GaN heterostructure. On a sapphire substrate, the following layer sequence was grown: a buffer layer, 2.8 μm undoped-GaN, 67-nm Si-doped GaN, 4.5-nm undoped GaN, 3.5-nm undoped AlGaN, 21-nm Si-doped AlGaN, 3.5-nm undoped AlGaN and finally a 3-nm GaN cap layer. Four-terminal longitudinal and Hall resistivities were measured using standard phase-sensitive ac lock-in techniques. The experiments were performed in a top-loading cryostat equipped with a superconducting magnet at a maximum field of 15 T. At T = 4 K, the electron density was $n = 1.12 \times 10^{13}$ cm^{-2} with a mobility of $\mu = 3400$ cm^2/Vs.

III. RESULTS AND DISCUSSION

Figure 1 shows longitudinal magnetoresistivity measurements, $\rho_{xx}(B)$, over a wide range of temperatures (4.682 K $\leq T \leq$ 80 K). At the lowest temperature T = 4.682 K, $\rho_{xx}(B)$ decreases with increasing B, and then show Shubnikov-de Haas (SdH) oscillations at even higher magnetic fields. We can see that with increasing temperature, the amplitudes of the SdH oscillations decrease. This is expected as SdH oscillations can be strongly damped due to strong electron-phonon scattering at high temperatures. It is worth mentioning that in our GaN electron system, the zero-field resistivity shows very little temperature dependence over the whole measurement range (4.682 K $\leq T \leq$ 80 K), consistent with our previous study [7]. This suggests that temperature-independent mechanisms, such as imperfection and dislocation scattering, dominates in our system. In comparison, electron-phonon scattering appears to play a much less important role in determining the transport properties of our GaN 2DEG at $B = 0$. We expect that with increasing measurement temperature, we are approaching the quasiclassical limit in which the Drude-Boltzmann transport is valid. From our experimental results, we can see that the low-field MR ($B < 8$ T) becomes weaker with increasing temperature due to decreased electron-electron interaction effects in this region.

We now turn to our main experimental findings. It is clear that at T = 80 K, $\rho_{xx}(B)$ becomes nominally B-independent which, is evidence for Drude-Boltzmann-like transport in the quasiclassical regime. As our measurement temperature is high enough, we are able to suppress electron-electron interactions, together with SdH oscillations, even at high magnetic fields. This allows us to observe the simplest case of Boltzmann-Drude-like electron transport, which appears to be elusive in the conventional transport data in the literature. We speculate that in the past, electron-electron interactions and strong modulation of the 2D density of states (DOS) in existing experiments might hinder the observation of Boltzmann-Drude-like transport, *i.e.*, of a B-independent longitudinal magnetoresistance. It is worth mentioning that over the whole measurement range, the carrier concentration determined from the Hall resistance is temperature-independent, as shown in Fig. 2. This suggests that we have a degenerate 2D electron system in which the Fermi level lies well above the conduction band bottom in GaN. This is consistent with the fact

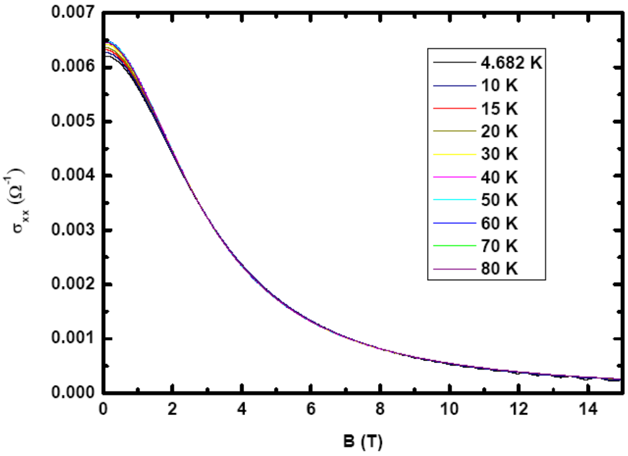

Fig. 3. Measured conductivity, σ_{xx}, over a wide range of temperatures (4.682 K $\leq T \leq$ 80 K).

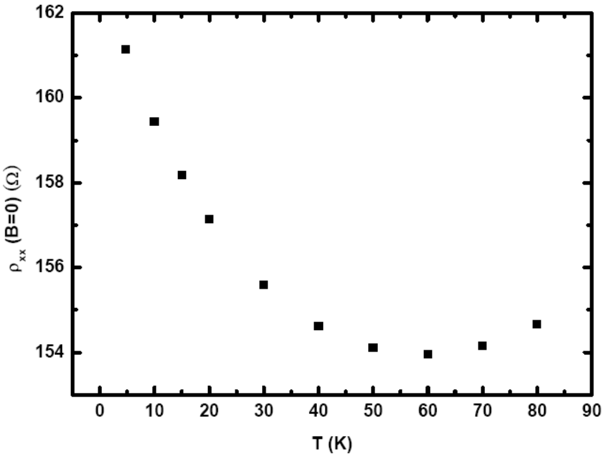

Fig. 4. Measured resistivity, ρ_{xx}, at $B = 0$ for various temperatures T.

that the carrier density of our GaN 2DEG is very high (1.12×10^{13} cm^{-2}).

In Fig. 3, we transform the magnetoresistivity result to the magnetoconductivity and the longitudinal conductivity as a magnetic field can be discussed by dividing it into parts. At very weak magnetic fields($<$ 0.1 T), the behavior of σ_{xx} presents a small decrease in the magnetoconductivity as the magnetic field decreases, which is attributed to weak localization.

From Eq. (3), we predict that $\sigma_{xx}(T)$ should have a logarithmic temperature dependence. We analyzed the magnetic field between 0.1 T and 0.3 T and calculated the slope of the σ_{xx}-vs-lnT curve. We find that the values of the slope in this range are close to one another. Therefore, we could predict that the contribution of the e-e interaction dominates in the intermediate magnetic field. At high magnetic fields, σ_{xx} begins to oscillate and the amplitude of the oscillation begins to increase with magnetic field due to Landau quantization. From Fig. 4 at zero magnetic field, the measured longitudinal resistivity, ρ_{xx}, decreases with increasing temperature over the temperature range 4 K $\leq T \leq$ 60 K, showing that our GaN 2DES appears to be a weak insulator. For $T > 60$ K, ρ_{xx} shows a small increase with increasing temperature due to an increase in electron-phonon scattering in this temperature range.

IV. CONCLUSIONS

In conclusion, we have performed transport measurements on a GaN/AlGaN 2DEG as a function of the magnetic field over a wide range of temperature. At low temperatures, the measured magnetoresistance decreases with increasing magnetic field, then exhibits Shubnikov-de Haas oscillations at higher magnetic fields. As the measurement temperature is increased, the magnetoresistance becomes weaker, and the SdH oscillations are heavily damped. At the highest temperature of 80 K, the longitudinal magnetoresistance becomes almost B-independent, which can be taken as evidence for Drude-Boltzmann-like transport in our 2D GaN electron system. We believe that it is the high measurement temperature that suppresses electron-electron interactions, together with the DOS modulation, and allows us to observe nominally zero MR.

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REFERENCES

[1] S. Nakamura, M. Senoh, N. Iwasa, S. Nagahama, Y. Yamada and T. Mukai, Jpn. J. Appl. Phys. **34**, L1332 (1995).

[2] G. E. Bulman, K. Doverspike, S. T. Sheppard, T. W. Weeks, H. S. Kong, H. M. Dieringer, J. A. Edmond, J. D. Brown, J. T. Swindell and J. F. Schetzina, Electron. Lett. **33**, 1556 (1997).

[3] M. P. Mack, A. Abare, M. Aizcorbe, P. Kozodoy, S. Keller, U. K. Mishra, L. Coldren and S. DenBaars, MRS Internet J. Nitride Semicond. Res. **2**, 41 (1997).

[4] A. Kuramata, K. Domen, R. Soejima, K. Horino, S. Kubota and T. Tanahashi, Jpn. J. Appl. Phys. **36**, L1130 (1997).

[5] D. R. Hang, C.-T. Liang, C. F. Huang, Y. H. Chang, Y. F. Chen, H. X. Jiang and J. Y. Lin, Appl. Phys. Lett. **79**, 66 (2001).

[6] D. R. Hang, C.-T. Liang, J. R. Juang, T.-Y. Huang, W. K. Hung, Y. F. Chen, G.-H. Kim, J. H. Lee and J. H. Lee, J. Appl. Phys. **93**, 2055 (2003).

[7] J. R. Juang, T.-Y. Huang, T.-M. Chen, M.-G. Lin, G.-H. Kim, Y. Lee, C.-T. Liang, D. R. Hang, Y. F. Chen and J.-I. Chyi, J. Appl. Phys. **94**, 3181 (2003).

[8] D. R. Hang, J. R. Juang, T.-Y. Huang, C.-T. Liang, W. K. Hung, Y. F. Chen, G.-H. Kim, Y. Lee, J. H. Lee, J. H. Lee and C. F. Huang, Physica E **22**, 578 (2004).

[9] J. R. Juang, D. R. Hang, M.-G. Lin, T.-Y. Huang, G.-H. Kim, C.-T. Liang, Y. F. Chen, W. K. Hung, W. H. Seo, Y. Lee and J. H. Lee, Chin. J. Phys. **42**, 629 (2004).

[10] K. S. Cho, T.-Y. Huang, C. P. Huang, Y. H. Chiu, C.-T. Liang, Y. F. Chen and I. Lo, J. Appl. Phys. **96**, 7370 (2004).

[11] K. S. Cho, T.-Y. Huang, H. S. Wang, M.-G. Lin, T.-M. Chen, C.-T. Liang, Y. F. Chen and I. Lo, Appl. Phys. Lett. **86**, 222102 (2005).

[12] D. R. Hang, C. F. Huang and Y. F. Chen, Phys. Stat. Sol. (c) **0**, 2323 (2003).

[13] O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff and L. F. Eastman, J. Appl. Phys. **85**, 3222 (1999).

[14] A. Ozgur, W. Kim, Z. Fan, A. Botchkarev, A. Salvador, S. N. Mohmmad, B. Sverdlov and H. Morkoc, Electron. Lett. **31**, 1389 (1995).

[15] M. A. Khan, Q. Chen, M. S. Shur, B. T. MsDermott, J. A. Higgins, J. Burm, W. J. Schaff and L. F. Eastman, IEEE Electron Dev. Lett. **17**, 584 (1996).

[16] S. C. Binari, J. M. Redwing, G. Kelner and W. Kruppa, Electron. Lett. **33**, 242 (1997).

[17] R. Gaska, Q. Chen, J. Yang, A. Osinsky, M. A. Khan and M. S. Shur, IEEE Electron Device Lett. **18**, 492 (1997).

[18] Y. F. Wu, S. Keller, P. Kozodoy, B. P. Keller, P. Parikh, D. Kapolnek, S. P. DenBaars, U. K. Mishra, IEEE Electron Device Lett. **18**, 290 (1997).

[19] R. Dimitrov, L. Wittmer, H. P. Felsl, A. Mitchell, O. Ambacher and M. Stutzmann, Phys. Stat. Sol. (a) **168**, R7 (1998).

[20] P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1984).

[21] S. Hikami, A. I. Larkin and Y. Nagaoka, Prog. Theor. Phys. **63**, 707 (1980).

[22] A. F. Brana, C. Diaz-Paniagua, F. Batallan, J. A. Garrido, E. Munoz and F. Omnes, J. Appl. Phys. **88**, 932 (2000).

[23] Y. Aharonov and D. Bohm, Phys. Rev. **115**, 485 (1959).

[24] B. L. Altshuler and A. G. Aronov in *Electron-Electron Interaction in Disordered Systems*, edited by A. L. Efros and M. Pollak (North-Holland, Amsterdam, 1985).

[25] G. Zala, B. N. Narozhny and I. L. Aleiner, Phys. Rev. B **64**, 214204 (2001).

[26] G. Zala, B. N. Narozhny and I. L. Aleiner, Phys. Rev. B **64**, 201201 (2001).

[27] A. Gold and V. T. Dolgopolov, Phys. Rev. B **33**, 1076 (1986).

[28] A. M. Finkelstein, Zh. Eksp. Teor. Fiz. **84**, 168 (1983)[Sov. Phys. JETP **57**, 97 (1983); Z. Phys. B: Condens. Matter **56**, 189 (1984)].

[29] C. Castellani, C. Di Castro, P. A. Lee and M. Ma, Phys. Rev. B **30**, 527 (1984); **30**, 1596 (1984); C. Castellani, C. Di Castro and P. A. Lee, *ibid.* **57**, R9381 (1998).

[30] L. Li, Y. Y. Proskuryakov, A. K. Savchenko, E. H. Linfield and D. A. Ritchie, Phys. Rev. Lett. **90**, 076802 (2003).

[31] A. Houghton, J. R. Senna and S. C. Ying, Phys. Rev. B **25**, 2196 (1982).

[32] S. Das Sarma and E. H. Hwang, Phys. Rev. Lett. **83**, 164 (1999).

[33] H.-I. Cho, G. M. Gusev, Z. D. Kvon, V. T. Renard, J.-H. Lee and J.-C. Portal, Phys. Rev. B **71**, 245323 (2005).

[34] For example, see A. D. Mirlin, J. Wilke, F. Evers, D. G. Polyakov and P. Wolfle, Phys. Rev. Lett. **83**, 2801 (1999).