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Non-monotonic Magnetoresistance in an AlGaN/GaN High-electron-mobility Transistor Structure in the Ballistic Region

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In this report, we will discuss the nonmonotonic magnetoresistance (MR) in an AlGaN/GaN high-electron-mobility transistor (HEMT) in a perpendicular magnetic field B in the ballistic region ($k_BT\tau/\hbar > 1$) and in the weakly-disordered limit ($k_Fl = 159 \gg 1$), where k_B, T, τ, $\hbar$, k_F, and l represent the Boltzmann constant, temperature, elastic scattering time, reduced Planck constant, Fermi wave vector and mean free path, respectively. The MR shows a local maximum between the weak localization (WL) and the Shubnikov-de Haas regions. In the low magnetic field regime, the quantum correction to the conductivity is proportional to $T^{-3/2}$, which is consistent with a recent theory [T. A. Sedrakyan, and M. E. Raikh, Phys. Rev. Lett. 100, 106806 (2008)]. According to our results, as the temperature is increased, the position of the MR maximum in B increases. These results cannot be explained by present theories. Moreover, in the high-magnetic-field regime, neither the magnetic and nor the temperature dependences of the observed MR is consistent with present theories. We, therefore, suggest that while some features of the observed nonmonotonic MR can be successfully explained, further experimental and theoretical studies are necessary to obtain a thorough understanding of the MR effects.

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I. INTRODUCTION

The III-V nitride semiconductor family (for example, GaN, InN, and AlN) continues to attract a great deal of worldwide interest [1–17] because the wide band-gaps that these compounds exhibit allow them to be utilized for a wide variety of optoelectronic applications [18]. In particular, GaN is probably the most studied III-V nitride semiconductor material due to its applications in high-frequency field-effect transistors [19] and in semiconductor light-emitting devices [20]. It is worth mentioning that the AlGaN/GaN high-electron mobility transistor (HEMT) structure is ideal for studying interesting physical phenomena, such as spin-related phenomena [16,21], electron-electron interactions (EEI) [22,23], and so on.

Recently, there has been renewed interest in the nonmonotonic magnetoresistance (MR) of two-dimensional electron gas (2DEG) systems when a magnetic field B is applied perpendicular to the plane of the 2DEG [24,25]. According to the classical Drude model, the longitudinal resistivity should not depend on the perpendicular magnetic field B [26]. However, many B-dependent MR effects have been observed in certain published experiments [27–32]. Two mechanisms, weak localization (WL) and electron-electron interaction (EEI), of the quantum corrections to the Drude conductivity have been stud-

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ied to explain the B-dependent MR. WL is due to the interference of electron waves propagating in opposite directions along closed paths, and it gives a quantum correction to the conductivity that depends on the temperature and the magnetic field at low fields $\mu B_{tr} < (k_F l)^{-1}$, where μ is the mobility. The transport magnetic field B_{tr} is found with the equation $\frac{\hbar}{4eD\tau}$, with electron charge e and the diffusion constant D. In the diffusive region, $k_B T\tau/\hbar < 1$, WL effect has been observed to decrease fast with increasing B, and to become weaker with increasing temperature, and finally to disappear in the ballistic region $k_B T\tau/\hbar \gg 1$.

The theory of EEI dealing with short-range potential fluctuations is widely discussed. Both T- and B- dependent quantum corrections to the conductivity due to EEI contribution can cover a wide range of B. In the diffusive region, the EEI correction is proportional to $\ln(\hbar/k_B T\tau)$ and grows in amplitude as the temperature decreases [33, 34]. Physically, this condition implies that the effective interaction time $\hbar/k_B T$ is larger than the momentum relaxation time τ. Therefore, two interacting electrons are scattered by many impurities. Zala *et al.* developed a theory of an EEI correction to the conductivity that bridged the theory between the diffusive and ballistic regions [35, 36]. It is based on observed interferences in electron waves. For instance, one of the electron waves is scattered by impurities, and the other is scattered by the potential oscillations (Friedel oscillations) created by another of the remaining electrons.

That EEI effect plays an important role in the transport properties of 2DEG systems is worth mentioning. It has been attracting a great deal of both theoretical and experimental attention. For $k_F l \gg 1$ systems, one of the theories of the EEI correctionm which has been suggested by Sedrakyan and Raikh (SR) [37], shows a positive quantum correction to the conductivity that is proportional to $T^{-3/2}$ in the weak magnetic field. The SR EEI correction to the conductivity can be described in the form of

$$\Delta\sigma^{SR}(B,T)/\sigma_0 = 4\lambda^2 \left(\frac{\pi k_B T}{\varepsilon_F}\right)^{\frac{3}{2}} F_2\left(\frac{\omega_c}{2\pi^{3/2}\Omega_T}\right), \quad (1)$$

where

$$\Omega_T = \frac{(k_B T)^{3/2}}{\hbar\varepsilon_F^{1/2}} \quad \text{and} \quad F_2(x) = \begin{cases} -0.7x^2, & x \ll 1 \\ -\frac{2x}{3}, & x \gg 1 \end{cases}$$

Here, $\omega_c = eB/m^*$ is the cyclotron frequency, where the effective mass m^* is equal to $0.23m_e$. ε_F is the Fermi energy, and $\lambda = 1 + 3F_0^\sigma/(1 + F_0^\sigma)$ is the interaction parameter in our case [24]. The EEI correction to conductivity has been shown to arise from the scattering of electrons on Friedel oscillations of the electron density around impurities. The impurity-induced Friedel oscillations contribution to the MR in the ballistic region is much more sensitive to the magnetic field [35,38]. The Friedel oscillation is limited by the length $r_T = v_F/2\pi T$ rather than by l. In our set-up, the magnetic field is applied perpendicularly to the plane of the 2DEG in the HEMT structure. The values of the magnetic field at the local maximum of MR increase linearly with increasing temperature in the ballistic regime. While some features of the observed MR can be explained by the recent SR theory, the magnetic field and the emperature dependences of the MR require further studies.

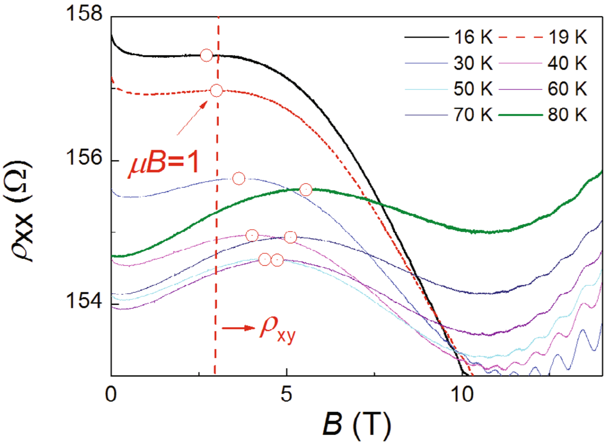

Fig. 1. (Color online) Magnetic field dependences of ρ_{xx} at various temperatures. The open circle symbol describes the local maximum values of ρ_{xx}(T). ρ_{xx}(19 K $\sim \hbar/k_B\tau$) has a maximum around $\mu_B = 1$.

II. EXPERIMENTS AND DISCUSSION

The sample is grown by using metal-organic chemical vapor deposition (MOCVD) on the sapphire substrate in the following layer sequence: a buffer layer, 2.8-μm undoped GaN layer, 67-nm Si-doped GaN layer, 4.5-nm unpdoped GaN layer, 3.5-nm undoped AlGaN layer, 21-nm Si-doped AlGaN layer, 3.5-nm undoped AlGaN layer and 3-nm GaN cap layer. The longitudinal and the Hall magnetoresistances were measured on Hall bars with length-to-width ratios of 5. The typical value of the current flow was 1 μA. At T = 4 K, the electron density n was 1.23 $\times$ 10^{13} cm^{-2} with a mobility of μ = 3128 cm^2/Vs.

We observed that the MR showed a local maximum in the ballistic region and that with increasing temperature, the position of the MR maximum in B increased as shown in Fig. 1. We plotted the variations of ρ_0 (B = 0) and ρ_{max} with temperature in Fig. 2(a). At 19 K($k_B T\tau/\hbar \sim$1), the MR has a maximum around μB_c = 1 ($B_c \sim$ 3 T). At temperatures above 19 K, the magnetic fields of the MR maxima, B_{max}, are larger than B_c. The B_{max} is linearly depends on the temperature, as shown in Fig. 2(b).

In order to further investigate the observed magnetoresistance peak, we have to consider both the WL and the EEI effects in our system. In a magnetic field, the clas-

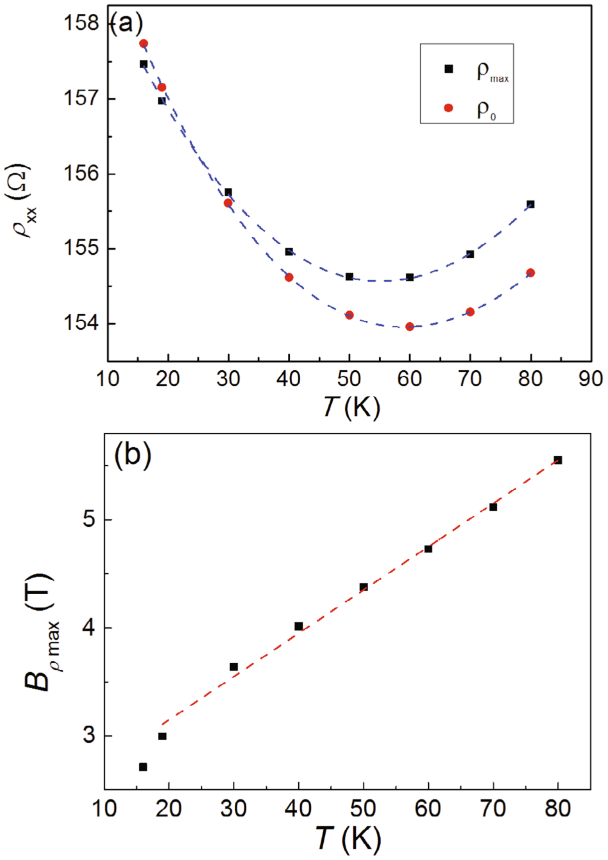

Fig. 2. (Color online) (a) Variations of ρ_0 ($B = 0$) and ρ_{max} with temperature. As $T > 19$ K $\sim \hbar/k_B\tau$, the magnetic fields of the MR maxima exceed in $\mu B = 1$. (b) The magnetic fields of the MR maxima vs. temperature. The MR shows a maximum, and with increasing temperature, the position of the MR maximum in B increases.

sical Drude conductivity tensor has the following form:

$$\sigma_D = \frac{ne\mu}{1+\mu^2B^2}\begin{pmatrix} 1 & \mu B \\ -\mu B & 1 \end{pmatrix}. \tag{2}$$

A general formula for the longitudinal magnetoconductivity is given by the expression:

$$\sigma_{xx} = \sigma_0 + \Delta\sigma_{xx}^{ee} + \Delta\sigma_{xx}^{WL}. \tag{3}$$

Here, $\sigma_0 = ne\mu$ is the Drude conductivity without a magnetic field; $\Delta\sigma_{xx}^{ee}$ and $\Delta\sigma_{xx}^{WL}$ are the EEI and the WL correction terms, respectively. The WL effect is suppressed by increasing the magnetic field over the critical field, $B_{tr} = \hbar/(2el^2) \sim 0.01$ T. For $B < B_{tr}$, the WL and the EEI effects can coexist. Therefore, we discuss the temperature dependence of the conductivity for $B \gg B_{tr}$, where the WL correction vanishes and the EEI correction is dominant.

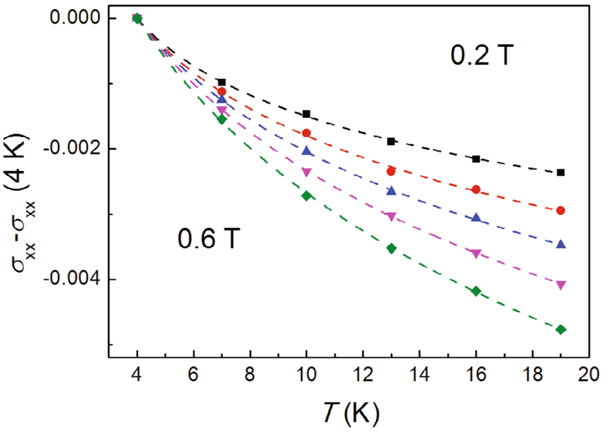

Fig. 3. (Color online) $\Delta\sigma_{xx}(B, T-4$ K) vs. T. From top to bottom, $B = 0.2$, 0.3, 0.4, 0.5, and 0.6 T. The dash lines are fitted by $\ln(k_BT\tau/\hbar)$ in the diffusive regime.

In the diffusive limit, the logarithmically divergent correction to the longitudinal conductivity is given by [33,34,39–41]:

$$\Delta\sigma_{xx}^{ee} = \frac{e^2}{2\pi^2\hbar}\ln\left(\frac{k_BT\tau}{\hbar}\right)\times\left[1+3\left(1-\frac{\ln(1+F_0^\sigma)}{F_0^\sigma}\right)\right]. \tag{4}$$

From Eqs. (3) and (4), $\Delta\sigma_{xx}$ shows logarithmic temperature dependence as presented in Fig/ 3. The results show $F_0^\sigma \sim 0.105$. If Eqs. (2) and (3) are considered with $\sigma_0 \gg \sigma_{xx}^{ee}$ and $\mu B < 1$ and if the WL effect is ignored, then the MR can be expressed as [18,30]:

$$\rho_{xx} \sim \frac{1}{\sigma_0} - \frac{1}{\sigma_0^2}\times(1-\mu^2B^2)\Delta\sigma_{xx}^{ee}. \tag{5}$$

Because $\Delta\sigma_{xx}^{ee} > 0$, ρ_{xx} ($B > 0$) is lower than ρ_{xx} ($B = 0$), which provides an explanation for the negative MR in the diffusive region.

We use Eq. (1) to fit the magnetoconductivity in the ballistic region, as shown in Fig. 4(a) and plot the T dependence of the magnetoconductivity for various weak magnetic fields, as shown in Fig. 4(b). According to Eqs. (1) and (5), the SR theory provides positive magnetoresistance that scales as $T^{-3/2}$. All these experimental results are consistent with the positive quantum correction to conductivity being proportional to $T^{-3/2}$ in weak field.

For high magnetic fields, the SR theory predicts that the MR will have a maximum at $\omega_c\tau = \mu B_c = 1/\sqrt{3}$. However, according to the experimental results, the MR has a maximum at $\mu B_c > 1$ for $T > 19$ K, and the MR maximum is shifted linearly with increasing temperature towards higher magnetic fields. In high fields, for $B > B_c$, the conductivity described by the SR theory does not saturate to $\sigma_D + \Delta\sigma_{xx}^{ee}(T)$, is proportional to B, and is temperature-independent. However, our experimental results show that σ is proportional to B^{-2} in high magnetic fields. As shown in Fig. 5, the scaled conductivity correction term shows a lnT dependence in the high-field region [29,42].

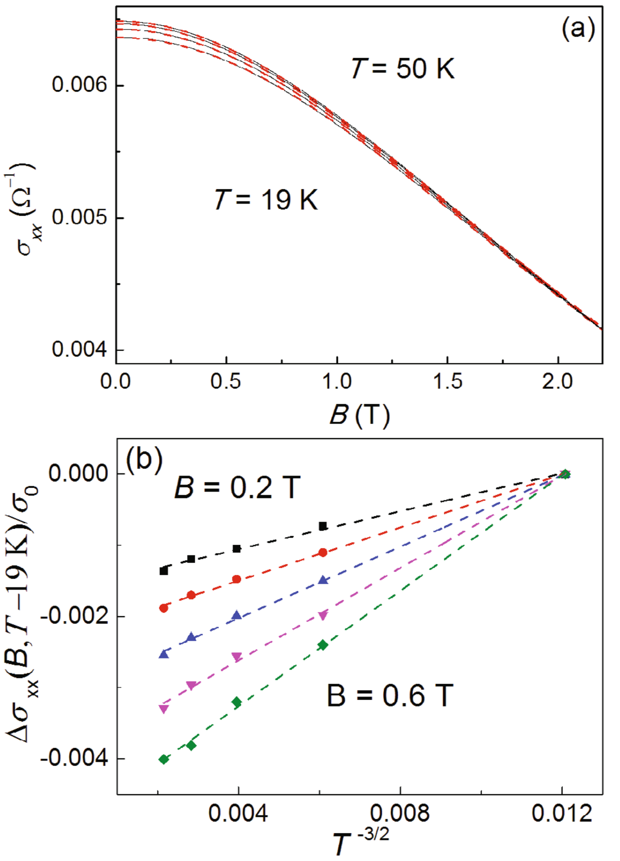

Fig. 4. (Color online) (a) Magnetic field dependences of σ_{xx} at various temperatures: 19, 30, 40, and 50 K. The dashed line describes the SR-EEI fitting. (b) $\Delta\sigma_{xx}(B, T-19$ K$)/\sigma_0$ vs. $T^{-3/2}$. From top to bottom: $B = 0.2$, 0.3, 0.4, 0.5, and 0.6 T. From right to left: $T = 19$, 30, 40, 50, and 60 K.

III. CONCLUSION

We have reported novel magnetoresistance in an AlGaN/GaN HEMT structure in the ballistic region with a weakly disordered limit. Then, we compared our experimental results with the Sedrakyan-Raikh theory [37]. The MR shows a maximum, and with increasing temperature, the position of the MR maximum in B increases. Moreover, the magnetic fields of the MR maxima exceed the SR theory's prediction. In weak fields, the negative magnetoresistance is caused by the WL correction whereas the EEI correction provides positive magnetoresistance. We have found that the temperature dependence of the EEI correction agrees with the SR theory in weak fields. Contrarily, in the high-field region, the experiment is not consistent with the prediction from the SR theory. The observation of the nonmonotonic MR shows that more considerations of EEI corrections are needed if the magnetotransport theory is to be improved.

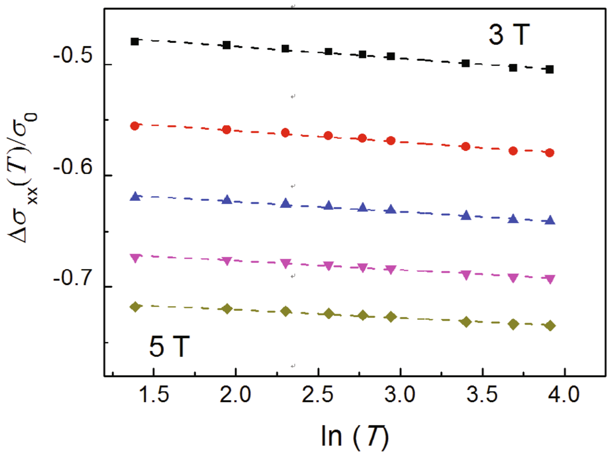

Fig. 5. (Color online) $\Delta\sigma_{xx}$ vs. ln T. From top to bottom: $B = 3$, 3.5, 4, 4.5, and 5 T. The dashed lines are linearly fitted. From left to right, $T = 4$, 7, 10, 13, 16, 19, 30, 40, and 50 K.

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