Electron-electron interactions in $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$ high electron mobility transistor structures grown on Si substrates

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We report on magnetotransport studies of $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$ high electron mobility transistor (HEMT) structures grown on *p*-type Si (111) substrates. A small but significant decrease of the Hall slope with increasing temperature is observed. Moreover, the converted conductivities reveal that the mobility of the HEMT shows a linear dependence on temperature. All these experimental results can be ascribed to electron-electron interaction (EEI) effects in $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structures grown on Si. The existence of EEI effects can be utilized to design and optimize GaN-based quantum devices on Si such as single-electron transistors and quantum point contacts since EEI effects can strongly modify the transport in semiconductor devices. © 2007 American Institute of Physics. [DOI: 10.1063/1.2430778]

Recently $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures have been attracting a great deal of both theoretical and experimental interest because of their applications in light-emitting diodes,^{1,2} in semiconductor lasers,^{3,4} in high-frequency field-effect transistors,⁵ in high-power microwave devices,⁶ and in high electron mobility transistors (HEMTs).⁷⁻¹⁴ It is worth mentioning that both piezoelectric and spontaneous polarization effects can be exploited to design a nominally undoped $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT with an extremely high electron density ($>10^{13} \text{ cm}^{-2}$).¹¹⁻¹⁴

It is now well known that at low temperatures T , the Coulomb interactions amongst conduction electrons can give rise to a quantum correction term to the classical Drude conductivity. Until recently, our understanding of the electron-electron interaction (EEI) corrections to the conductivity of a weakly disordered two-dimensional electron gas was based on the seemingly unrelated theories developed for two opposite regions: the diffusive region $k_B T \tau / \hbar \ll 1$ and the ballistic region $k_B T \tau / \hbar \gg 1$, where k_B is the Boltzmann constant and τ is the elastic mean free time. Zala, Narozhny, and Aleiner¹⁵ developed a theory of an electron-electron interaction correction to the conductivity that bridged the gap between the two theories known previously. 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. According to the theory of EEI in the diffusive limit, the magnetoresistivity ρ_{xx} is given by¹⁶

$$\rho_{xx} \approx \rho_0 (1 - \mu^2 B^2) \Delta \sigma_{ee}(T), \quad (1)$$

where ρ_0 is the classical Drude resistivity at zero magnetic field, μ is the Hall mobility, and $\Delta \sigma_{ee}(T)$ is the correction term due to EEI at different temperatures. We note that Eq.

(1) predicts negative parabolic magnetoresistivity. In addition to the correction term $\Delta \sigma_{ee}(T)$, it is now well established that electron-electron interactions can cause a logarithmic T correction to the Hall resistance.¹⁷ It is worth pointing out that EEI effects not only play an important role in the transport in electronic devices, but are also believed to be important to the apparent metallic behavior in two dimensions.

$\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structures are usually grown on sapphire. Although Si can be considered as an alternative^{18,19} to commercial sapphire substrates for GaN-based devices, the large thermal mismatch ($\sim 54\%$) and lattice mismatch ($\sim 17\%$) between Si and GaN hinder the growth of high-quality GaN layers on Si. Recently we have shown that by introducing an ultrathin SiN film during the crystal growth, the Hall mobility of an $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT on Si can be greatly increased (more than three times).^{20,21} These $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMTs grown on silicon are compatible with complementary-metal-oxide-semiconductor (CMOS) technology and have promising device applications. Given this, it is highly desirable to understand the fundamental physics of transport in those HEMT structures in order to fully realize their potentials. In particular, EEI effects in an $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structure grown on Si are still largely unexplored, and the purpose of this letter is to study such effects. We shall demonstrate that there exists a small, but significant decrease of the Hall slope with increasing temperature. Such a change is not due to the change in the carrier density with temperature, but can be ascribed to the EEI effect. Our experimental results also reveal a linear dependence of the mobility, which is due to the ballistic contribution of the EEI effect. The existence of the EEI effects in $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structure grown on Si could be utilized to design and optimize GaN-based quantum devices such as quantum point contacts²² and single-electron transistors.²³

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FIG. 1. (Color online) (a) Hall resistivity measurements ρ_{xy} as a function of magnetic field B at various temperatures for sample A. From top to bottom: $T=0.27, 1.04, 1.55, 3.3, 5.5, 8.0, 10, 15,$ and 20 K, respectively. The inset shows the Hall slope as a function of $\ln T$. (b) Hall resistivity measurements ρ_{xy} as a function of magnetic field B at various temperatures for sample A. From top to bottom: $T=0.27, 1.20, 3.07, 10,$ and 20 K, respectively. The inset shows the Hall slope as a function of $\ln T$.

Two devices, sample A and sample B, are studied in this work. These two samples have almost identical structures except that sample B has been SiN treated and thus has a much higher Hall mobility. The details and growth of these two samples have been reported elsewhere.^{20,21} The carrier density n of sample A is $\sim 9.5 \times 10^{12} \text{ cm}^{-2}$ with a Hall mobility of $\sim 700 \text{ cm}^2/\text{Vs}$, whereas the carrier density of sample B is $\sim 9.4 \times 10^{12} \text{ cm}^{-2}$ with a Hall mobility of $\sim 2500 \text{ cm}^2/\text{Vs}$ at $T=0.27$ K. The carrier density of our system appears to be higher than that of an undoped $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$ HEMT structure grown on sapphire. A possible reason for this could be a stronger strain introduced during the crystal growth. As the carrier density is higher in our system, the electrons may not be totally confined, and electrons near or in the barrier will suffer from alloy potential fluctuations. Four-terminal longitudinal resistivity and Hall measurements were performed in a top-loading He^3 cryostat over a wide range of temperature $0.27 \text{ K} \leq T \leq 70 \text{ K}$ using standard phase-sensitive ac lock-in techniques.

Figures 1(a) and 1(b) show the Hall resistivity measurements for sample A and sample B at various temperatures T . The data reveal a small, but significant decrease of the Hall slope with increasing temperature T . As shown in the insets to Figs. 1(a) and 1(b), the Hall coefficients R_H show logarithmic T dependences in both cases. All these experimental results are consistent with the electron-electron interaction effects in a disordered system.¹⁷

One might argue that the decreases of the Hall slopes shown in Figs. 1(a) and 1(b) are due to the changes of the electron concentrations with increasing T . Figures 2(a) and 2(b) show $\Delta\rho_{xx} = \rho_{xx}(B) - \rho_{xx}(B=0)$ as a function of B^2 at various temperatures. For both sample A and sample B, $\rho_{xx}(B) - \rho_{xx}(B=0)$ decreases with increasing B . For sample B, at the high-field regime, there exist Shubnikov-de Haas (SdH) oscillations. It becomes immediately evident that the

FIG. 2. (Color online) (a) $\Delta\rho_{xx} = \rho_{xx}(B) - \rho_{xx}(B=0)$ as a function of B^2 at various temperatures for Sample A. From bottom to top: $T=0.27, 1.04, 1.55, 3.3, 5.5, 8.0, 10, 15,$ and 20 K, respectively. The inset shows the converted $\sigma_{xy}(B)$. The red curve corresponds to the fit to Eq. (3). (b) $\Delta\rho_{xx} = \rho_{xx}(B) - \rho_{xx}(B=0)$ as a function of B^2 at various temperatures for sample B. From bottom to top: $T=0.27, 1.20, 3.07, 10,$ and 20 K, respectively. The top inset shows the converted $\sigma_{xy}(B)$ at $T=0.27$ K. The red curve corresponds to the fit to Eq. (3). (b) The bottom inset shows the converted $\sigma_{xx}(B)$ at $T=0.27$ K. The red curve corresponds to the fit to Eq. (4).

extrema of SdH oscillations remain fixed in B^2 , and hence fixed in B . Therefore the electron densities determined from the observed SdH oscillations are T independent over the whole measurement range. Therefore we are able to demonstrate that the observed decrease of the Hall slope with increasing temperature shown in Fig. 1(b) cannot be due to the change in n , but must be due to EEI effects. As for sample A, it is not possible to observe SdH oscillations due to the existence of strong disorder broadening. Nevertheless, given the fact that sample A and sample B have almost identical structures and approximately the same carrier densities, it is believed that the observed decrease of the Hall slope with increasing T shown in Fig. 1(a) is also due to electron-electron interaction effects, not due to the change in n at different temperatures.

Over the whole measurement range, $\Delta\rho_{xx}$ does not show a good B^2 dependence for sample A. On the other hand, we can see that as shown in Fig. 2(b) for $10 \leq B^2 \leq 50$, $\Delta\rho_{xx}$ shows a good B^2 dependence for sample B, consistent with Eq. (1). Recently it has been shown that such an equation should be rewritten when considering the renormalization of the mobility $\mu' = \mu + \delta\mu$ caused by the ballistic contribution of the EEI correction.²⁴

FIG. 3. (Color online) Renormalized mobility μ' determined using Eqs. (2)–(4) as a function of T for sample B, respectively. In all cases, μ' shows a linear T dependence for $T \leq 10$ K.

$$\rho_{xx}(B, T) \approx \frac{1}{en\mu'} - \frac{1}{(en\mu')^2} (1 - (\mu'B)^2) \Delta\sigma_{ee}^d(T). \quad (2)$$

Moreover, by converting the experimental data into the conductivities, it is also possible to determine μ' :²⁴

$$\sigma_{xx} \equiv \frac{en\mu'}{1 + (\mu'B)^2} + \Delta\sigma_{ee}^d, \quad (3)$$

$$\sigma_{xy} \equiv \frac{en(\mu')^2 B}{1 + (\mu'B)^2}. \quad (4)$$

The inset to Fig. 2(a) and the top inset to Fig. 2(b) show the converted data σ_{xy} at $T=0.27$ K, together with the fits for sample A and sample B, respectively. We can see that the fit for sample B is considerably better than that for sample A, therefore we concentrate on sample B. The bottom inset to Fig. 2(b) shows the converted data σ_{xx} and the excellent fit using Eq. (4) for sample B. As only data obtained on sample B show reasonable fits to the model, we only show the determined μ' from three different methods using Eqs. (2)–(4), respectively, as displayed in Fig. 3. There is an excellent agreement between fits using Eqs. (2) and (4). The determined μ' using Eq. (3) is somewhat smaller than those determined by Eqs. (2) and (4). Nevertheless, in all cases, we note that μ' shows an approximately linear T dependence in the low temperature range $T \leq 10$ K, consistent with the renormalization of the mobility due to the ballistic contribution of the EEI effect.²⁴ The decrease of μ' at high temperatures is probably due to the increased electron-phonon scattering.⁷

In conclusion, we have presented experimental evidence for electron-electron interaction effects in $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$ HEMT structures grown on Si (111) substrates. This is supported by the observed logarithmic T dependence of the Hall slopes, together with the observed linear T dependence of the renormalized mobility. Such a fundamental understanding could be helpful in designing and optimizing GaN-based devices on Si which have great optoelectronic device applications and, most importantly, are compatible with the well-established silicon CMOS technology.

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