Correlation Field Analysis of Magnetoresistance of GaN/AlGa_N Heterostructure Grown on Si Substrate

Li-Hung LIN*, Shiou-Shian HAN, Kui-Ming CHEN, Zhi-Yao ZHANG¹, Kuang Yao CHEN¹, J. Z. HUANG¹, Zhi-Hao SUN¹, C.-T. LIANG^{1,2}, N. C. CHEN³, P. H. CHANG³, and Chin-An CHANG³

Institute of Optoelectronics and Solid State Electronics, National Chiayi University, Chiayi 60004, Taiwan

¹*Department of Physics, National Taiwan University, Taipei 10617, Taiwan*

²*Institute of Astrophysics, National Taiwan University, Taipei 10617, Taiwan*

³*Institute of Electro-Optical Engineering, Chang Gung University, Taoyuan 300, Taiwan*

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We analyze the conductance fluctuations for a bulk two-dimensional electron system in a GaN/Al_{0.15}Ga_{0.85}N heterostructure grown on a p-type Si(111) substrate, and calculate the correlation field B_c with the autocorrelation function $F(\Delta B) = \langle \delta G(B + \Delta B) - \delta G(B) \rangle$, in the temperature range $0.27 \leq T \leq 3$ K, which is employed as a self-thermometer to obtain the effective carrier temperature T_e as a function of the measurement current I . We find that the temperature dependence agrees well with simple expectations for universal conductance fluctuations in metals, while the observed amplitude is reduced. In the study of hot-carrier phenomena, we also obtain $T_e \sim I^{0.5}$, which agrees with some theoretical prediction.

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KEYWORDS: GaN, HEMT, conductance fluctuation, hot carrier, current scaling

1. Introduction

GaN/AlGa_N heterostructures have been attracting a great deal of experimental and theoretical interest because of their applications in light-emitting diodes,^{1,2} high-power microwave devices,³ high-frequency field-effect transistors,⁴ semiconductor lasers,^{5,6} and high-electron-mobility transistors.^{7–10} GaN/AlGa_N heterostructures are usually grown on sapphire. However, Si can also be regarded as an alternative to commercial sapphire substrates for GaN-based semiconductor devices because of its low cost and large wafer size. Because of the large lattice (17%) and thermal (54%) mismatches between Si and GaN, high-quality GaN films are extremely difficult to grow on Si. An intermediate nucleation layer of AlN grown on top of Si can greatly improve the quality of subsequently grown GaN films.^{11,12} Recently, it has been shown that by introducing an ultrathin SiN_x film during crystal growth, the Hall mobility of a GaN/Al_{0.15}Ga_{0.85}N heterostructure on Si could be markedly increased (>3 times).^{13–15} These GaN/Al_{0.15}Ga_{0.85}N heterostructures grown on Si are compatible with complementary metal-oxide-semiconductor technology and have promising device applications, making it useful in understanding the fundamental physics of these heterostructures.

Electron heating is a central problem in semiconductor devices, both in device applications and in research on solid state physics. Hot carriers are created when carriers are accelerated by an electric field if the energy transport between carriers and metal lattice is weaker than that from the lattice to the surroundings. At liquid-helium temperature, electrically accelerated carriers can be heated to a higher temperature, T_e , while phonons stay at a cooler temperature, T_L , in a ballistic or quasi-ballistic transport system, which is caused by the carrier-phonon energy exchange rate being lower than that at higher temperature. In some theoretical and experimental studies of GaAs/AlGaAs heterostructures and other two-dimensional electron systems (2DESs), the power law $T_e \sim I^\alpha$ arises in hot-carrier phenomena, where I

is the current.^{16,17} The widths of peaks or derivatives of plateaus in magnetoresistance (MR) are frequently used as self-thermometers for estimating carrier temperature T_e .

Conductance fluctuations may be one of the most prominent phenomena in mesoscopic structures. For diffusive conducting systems at sufficiently low temperatures, these so-called universal conductance fluctuations (UCFs) have a characteristic amplitude, $\sim e^2/h$, independent of sample size and material, and they are generally thought to be well understood.¹⁸ Similar conductance fluctuations are also observed and discussed in mesoscopic quantum Hall (QH) systems,^{19–28} quantum wires,^{29–32} quantum point contacts,^{33,34} open cavity (quantum dot) systems,^{35–42} and loop systems.⁴³ Interpretations of different experiments include the modification of UCF in high field,^{19,20} the tunneling between opposite edge states through bulk inhomogeneities,^{22–24} the influences of charging effects,^{25,26} and the network of compressible-incompressible regions.²⁷ In these studies of conductance fluctuations, the autocorrelation function $F(\Delta B) = \langle \delta G(B + \Delta B) - \delta G(B) \rangle$ of MR fluctuations $\delta G(B)$ is frequently employed, where the angle brackets denote the average over all magnetic fields. Some physical amounts can be estimated by the analyses of conductance fluctuations, including the correlation field B_c , which is defined as $F(B_c) = F(0)/2$. The dephasing length $L_\phi(T)$ of carriers, as an example, can be estimated with $B_c(T) = \phi_0/[L_\phi(T)]^2$, where the magnetic flux quantum ϕ_0 is given by h/e .²¹

In this study, we use B_c for studying the GaN/Al_{0.15}Ga_{0.85}N heterostructure on Si and use B_c as a self-thermometer to find the scaling relation between the measurement current I and the effective carrier temperature T_e , and discuss the hot-carrier phenomena in the system. Many works have been conducted on microscopic scattering processes these years. A model of scaling in the integer quantum Hall region when a current I is applied was introduced by Polyakov and Shklovskii,⁴⁴ and a recent study showed that an effective electron temperature $T_e \sim I^{0.5}$ can be deduced by combining temperature scaling and current scaling of the amplitude or peak broadening of Shubnikov–

*E-mail address: lihung@mail.nyu.edu.tw

de Haas (SdH) oscillation in MR.^{16,17} The experimental results $T_e \sim I^{0.5}$ have been reported for GaAs/AlGaAs and InGaAs/InP 2DESs.^{16,17,45}

2. Experimental Methods

The samples studied in this work were grown using metal-organic vapor phase epitaxy in an Aixtron RF-S system.¹⁴ The following layer sequences was grown on p-type Si(111) substrates: 2.5-nm low-temperature (LT) AlN, 2.5-nm high-temperature (HT) AlN, an ultra-thin SiN_x (only in sample B), 350-nm GaN, 12-nm LT AlN, 12-nm HT AlN, 400-nm GaN, and 30-nm Al_{0.15}Ga_{0.85}N, where LT and HT AlN layers correspond to AlN layers grown at 620 and 1050 °C, respectively. In this work, all the GaN and AlGaAs layers were grown at 1050 °C with a Ga polarity. The SiN_x treatment of sample B was introduced by SiH₄ flow of 50 sccm diluted to 100 ppm with H₂. Growth pressure and temperature were kept at 100 mbar and 1050 °C, respectively, for 5 s. The SiN_x treatment is believed to help reduce the dislocation density in the GaN layer, improving both the quality of the GaN layer and the mobility of the 2DES in sample B. The carrier concentrations of the 2DESs in samples A and B are 9.2×10^{12} and $9.4 \times 10^{12} \text{ cm}^{-2}$ respectively, with Hall mobilities of ~ 700 and $\sim 2500 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ respectively at $T = 0.27 \text{ K}$. The carrier concentrations of our systems appear to be slightly higher than that of an undoped GaN/AlGaAs heterostructure grown on sapphire, which may be caused by the stronger strain introduced during the crystal growth. The four-terminal MR of $4 \times 4 \text{ mm}^2$ 2DES bulks in the van der Pauw method was measured in a ³He cryostat over a wide range of temperatures $0.27 \leq T \leq 70 \text{ K}$, by using standard phase-sensitive ac lock-in techniques, and the magnetic field $-15 \leq B \leq 15 \text{ T}$ was generated by a superconducting magnet, which applies magnetic field perpendicular to the substrates.

3. Results and Discussion

The longitudinal MR of sample A (without SiN_x treatment) shows no clear signal of SdH oscillations even at low temperatures and high magnetic fields, which implies that the Landau level in this sample may be broadened by defects. On the other hand, sample B (with SiN_x treatment) shows SdH oscillations at low temperatures $< 10 \text{ K}$ (Fig. 1). The enhancement of the what of sample B has also been studied by transmission electron microscopy in our previous work, where sample B shows a lower dislocation density than sample A. We concentrate on the MR analysis of sample B in the QH-conducting regime where SdH oscillations can be observed.

After the subtraction of the MR background of sample B, MR fluctuations $\delta G(B)$ were obtained in both the QH-conducting regime ($B > 4.5 \text{ T}$) and the insulating regime ($B < 4.5 \text{ T}$). The MR fluctuations are $\sim (0.01)e^2/h$, smaller than typical UCF for one order (Fig. 1, inset). On the other hand, MR fluctuations usually average out in a homogeneous heterostructure, but temperature-dependent MR fluctuations are observed in sample B, which may be caused by inhomogeneities in the heterostructure. The temperature dependence of B_c is shown in Fig. 2, and $B_c(T)$ increases with temperature in the QH-conducting regime. This shows that $L_\varphi(T)$ decreases with temperature, thus implying the

Fig. 1. (Color online) The longitudinal MRs of sample B at 0.27, 1.2, 3.1, 10.0, and 20 K are shown in series. When temperature is increased, resistance increases in the region $B > 5 \text{ T}$ and decreases in the region $B < 4 \text{ T}$. The inset shows MR fluctuations at 0.27 K.

Fig. 2. Correlation fields B_c of sample B are plotted as a function of T . The three series for $0.2 < B < 4 \text{ T}$, $5 < B < 10 \text{ T}$, and $10 < B < 15 \text{ T}$ are marked by $\circ$, $\square$, and $\diamond$, respectively. The inset shows an example of autocorrelation functions and correlation fields.

origin of quantum phase coherence in this phenomenon. However, the increase in B_c is not clear in the insulating regime, which may be caused by potential fluctuation by defects. To determine the effective temperature of carriers in hot-carrier phenomena, we also measured the current dependence of MR at the base temperature, and thus we obtained $B_c(I)$, which is shown in Fig. 3. $B_c(I)$ shows the tendency of increase in the QH-conducting regime, but shows no clear increase in the insulating regime. We employed B_c as a self-thermometer, and thus obtained the effective carrier temperature in the QH-conducting regime, which is shown in Fig. 4. The current scaling of carrier temperature shows the power law $T_e \sim I^{0.5}$, which is similar to the result of previous theoretical and experimental studies of GaAs/AlGaAs and InGaAs/InP 2DESs.^{16,17,45}

4. Conclusions

In conclusion, we have presented experimental results of the electrical measurements of GaN/Al_{0.15}Ga_{0.85}N heterostructures grown on Si. The SiN_x treatment enhanced the quality of the 2DES, where a clear SdH oscillation can be observed. We also employed autocorrelation analysis of conductance fluctuation, and thus obtained the correlation field B_c as function of T_e and I . In the QH-conducting regime, B_c increases as T_e or I increases. We also used B_c as a self-thermometer in the QH-conducting regime, and the

Fig. 3. Correlation fields B_c of sample B at base temperature are plotted as the functions of I . The three series for $0.2 < B < 4$ T, $5 < B < 10$ T, and $10 < B < 15$ T are marked by $\circ$, $\square$, and $\diamond$, respectively.

Fig. 4. Effective carrier temperature of sample B is plotted as a function of I , which is obtained from the results in Figs. 2 and 3. The straight line shows the power law $T_e \sim I^{0.54}$.

current scaling of carrier temperature $T_e \sim I^{0.5}$ is obtained, which agrees with the results of theoretical and experimental studies of GaAs/AlGaAs and InGaAs/InP 2DESs.^{16,17,45)}

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