Electron heating in $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$ heterostructures grown on p-type Si

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Abstract

The transport behaviors of two GaN/AlGaIn two-dimensional electron systems (2DESs) grown on Si substrates were studied, and a SiN_x treatment employed in sample fabrication enhanced the conductance of one of the 2DESs. We study the electron heating effect in the 2DESs experimentally, with resistances as self-thermometers. The relation of $T_e \sim I^{1.42}$ was obtained, which is in contrast to $T_e \sim I^{0.5}$ in the resistivity peaks in a GaAs/AlGaAs 2DES. This may be caused by the scattering effect in this sample.

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1. Introduction

Recently GaN/AlGaIn heterostructures have attracted much interest because of their application in electrical, light-emitting devices, and high-electron-mobility transistors (HEMTs) [1–14]. The electronic properties of a GaN-based device are governed by the two-dimensional electron system (2DES) formed in the GaN/AlGaIn quantum well. Different from the 2DESs of other materials, e.g., Si metal-oxide-semiconductor field-effect transistors (MOSFETs) and GaAs/AlGaAs HEMTs, there may be no doping in GaN and AlGaIn in a GaN/AlGaIn heterostructure as a result of spontaneous and piezoelectric polarization effects.

GaN could be grown on either Si or sapphire, in spite of their large lattice mismatches with GaN [11], because of a lack of homoepitaxial substrates. Needless to say, Si is an

attractive substrate for GaN-based devices due to its high quality and availability. However, special techniques are required for growing GaN films on Si. For example, employing AlN as an intermediate layer has reduced the lattice mismatch and stress between GaN and Si. In addition, some experiments showed that inserting thin SiN_x film could reduce the stress of GaN, and thus improve the quality of 2DESs [11–14].

Hot carriers are created when the carriers are accelerated by electric field, if the energy exchange rate between carriers and lattice is less than the rate between lattice and the surroundings. At liquid helium temperature, the electrically accelerated carriers reach a higher temperature T_e while phonons are at cooler temperature T_L in a ballistic or quasi-ballistic transport system, caused by the lower carrier-phonon energy exchange rate in comparison with the rate at higher temperature.

The study of hot-carrier phenomena in 2DESs is usually performed by means of analyzing the longitudinal and Hall resistivities, ρ_{xx} and ρ_{xy} . It was found that the maximum derivative of the Hall resistivity with respect to the

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magnetic field $d\rho_{xy}/dB|_{\max}$ showed a temperature scaling relation according to a power law $d\rho_{xy}/dB|_{\max} \sim T_L^{-\kappa}$, and similarly for the half width of the inverse-longitudinal-resistivity peaks $(\Delta B)^{-1} \sim T_L^{-\kappa}$ for ρ_{xx} in Shubnikov–de Haas oscillations (SdHOs), since the smearing of Landau levels. By increasing measuring current I , the hot-carrier phenomena and current scaling could be analyzed. A characteristic current I_0 exists for each T_L , below which $d\rho_{xy}/dB|_{\max}$ (or $(\Delta B)^{-1}$) remains constant, and above which $d\rho_{xy}/dB|_{\max}$ (or $(\Delta B)^{-1}$) merges into a power-law relation. Thus the current scaling $d\rho_{xy}/dB|_{\max} \sim I^{-\beta}$ was obtained, and such experimental results were reported for many 2DESs. Such a power-law relation can be found also in T scaling, and the effective carrier temperature is given by $T_e \sim I^\alpha$. The experimental result $\alpha \approx 0.5$ independent of Landau levels and spin degeneracy was reported on GaAs/AlGaAs and InGaAs/InP 2DESs.

2. Experiment

Two samples, Sample A and Sample B, are studied in this work. These two samples were grown by metal-organic vapor-phase epitaxy (MOVPE) using an Aixtron RF-S system. For Sample A, the following layer sequence was grown on a p-type Si (111) substrate: 2.5 nm low-temperature (LT) AlN, 2.5 nm high-temperature (HT) AlN, 350 nm GaN, 12 nm LT AlN, 12 nm HT AlN, 400 nm GaN, and 30 nm $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$, where LT and HT AlN correspond to AlN layers grown at 620 and 1050 °C, respectively. In this work, all the GaN and AlGaIn layers were grown at 1050 °C and are Ga-polarity. The structure of Sample B is identical to that of Sample A except that an ultra-thin SiN_x layer was grown between the 2.5 nm AlN and 350 nm GaN. This SiN_x treatment is introduced by using SiH_4 flow of 50 sccm diluted to 100 ppm with H_2 . The growth temperature was kept at a pressure of 100 mbar and a temperature of 1050 °C for 5 s. According to the high-resolution TEM studies, we are not able to detect any SiN_x layer in a SiN_x -treated sample. The SiN_x treatment is thought to help the reduction of dislocation density in the GaN layer, improving both the quality of the GaN layer and hence the mobility of the 2DES [12]. The carrier density of Sample A is $9.2 \times 10^{12} \text{ cm}^{-2}$ with a mobility of $\approx 700 \text{ cm}^2/\text{Vs}$ whereas the carrier density of Sample B is $9.4 \times 10^{12} \text{ cm}^{-2}$ with a mobility of $\approx 2500 \text{ cm}^2/\text{Vs}$ at $T = 0.27 \text{ K}$. Four-terminal resistance and Hall measurements were performed in a top-loading He^3 cryostat over a wide range of temperature 0.27–60 K using standard phase-sensitive AC lock-in amplifier techniques. The magnetic field 0–15 T perpendicular to the 2DESs are applied with a superconductor magnet.

In the experiment without magnetic field, the temperature-dependent resistances were also employed as a self-thermometer to estimate effective carrier temperatures. The resistance was measured with low power (current $\sim 1 \mu\text{A}$) applied firstly while the temperature was being increased,

and then higher power was applied at base temperature. The effective temperature was extracted from these data of parameter-dependent resistance.

3. Results and discussion

Fig. 1 shows longitudinal resistivity measurements as a function of magnetic field for Sample A at different temperatures. Due to the strong disorder within this sample, we are not able to observe SdHOs as the Landau levels are strongly broadened. There exists an approximately T -independent point at around $B \sim 10.6 \text{ T}$, which could be ascribed to a weak insulator-quantum Hall transition [15,16].

Fig. 2 shows longitudinal resistivity measurements as a function of magnetic field for Sample B, which was SiN treated, at different temperatures. We can see clear SdHOs in the high-field regime which persist up to around $T = 20 \text{ K}$. The zero-field resistivity of Sample B is about four times less than that of Sample A. Moreover, the measured mobility of Sample B is about three times higher than that of Sample A. Most importantly, clear SdHOs are now observable in Sample B, which was SiN treated. All these experimental results demonstrate that the SiN treatment technique improves the transport behavior of our AlGaIn/GaN HEMT structure.

We now turn to our main experimental results. Fig. 3(a) shows the resistance of Sample A as a function of temperature when a low current is applied. In Fig. 3(b), we show the resistance of Sample A as a function of current when the lattice temperature is fixed at $T = 0.27 \text{ K}$. By using the resistance as a self-thermometer and comparing the data shown in Figs. 3(a and b), we are able to obtain the electron temperature as a function of current as displayed in Fig. 3(c). We can see that for $I < 10 \mu\text{A}$, the electron temperature is approximately constant. This implies that no significant electron heating occurs for $I < 10 \mu\text{A}$. For $I > 10 \mu\text{A}$, we obtain the relation $T_e \sim I^{1.42}$, in contrast to $T_e \sim I^{0.5}$ in the spin-split resistivity peaks in a GaAs/AlGaAs 2DES. This may be caused by the scattering effect in this sample. The energy relaxation behaviors of

Fig. 1. Longitudinal magnetoresistivity measurements for Sample A at different temperatures.

Fig. 2. Longitudinal magnetoresistivity measurements for Sample B (SiN treated) at different temperatures.

Fig. 3. For Sample A, (a) resistance is shown as a function of temperature, (b) resistance is shown as a function of current, (c) effective temperature is shown as a function of current, which was extracted from (a) and (b).

our 2DESs containing dislocations, defects, and traps may be important.

In the study of Sample B, we analyzed the amplitude of SdHOs in $\rho_{xx}(B)$. In the magnetic field near $B = 14$ T, the effective temperature of heated carriers is increasing with the current, but no clear current scaling relation was found as shown in Fig. 4. At present, the physical origin for this effect is unclear but we speculate that energy relaxation behaviors of our 2DESs containing charged dislocations and defects may play a role in this.

Fig. 4. Effective temperatures are shown as a function of current of Sample B, which are obtained by analyzing the amplitude of SdHO in longitudinal magnetoresistance at $B = 14$ T.

4. Summary

The transport behaviors of two GaN/AlGaAs 2DESs grown on Si substrates were studied, and the comparison of the results shows that the device quality was improved by the application of SiN_x treatment. We study the electron heating effect in the 2DESs experimentally, with resistances or amplitudes of SdHOs as self-thermometers. The relation $T_e \sim I^{1.42}$ was obtained in a sample when $B = 0$, which is in contrast to $T_e \sim I^{0.5}$ in the resistivity peaks in a GaAs/AlGaAs 2DES. Since GaN is known to be a piezoelectric material, this may be caused by the scattering effect in this sample.

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