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Study on mobility enhancement in MOVPE-grown AlGaN/AlN/GaN HEMT structures using a thin AlN interfacial layer

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Abstract

$Al_{0.26}Ga_{0.74}N$/AlN/GaN high-electron-mobility transistor (HEMT) structures with AlN interfacial layers of various thicknesses were grown on 100-mm-diameter sapphire substrates by metalorganic vapor phase epitaxy, and their structural and electrical properties were characterized. A sample with an optimum AlN layer thickness of 1.0 nm showed a highly enhanced Hall mobility (μ_{Hall}) of 1770 cm^2/Vs with a low sheet resistance (ρ_s) of 365 Ω/sq. (2DEG density $n_s = 1.0 \times 10^{13}/cm^2$) at room temperature compared with those of a sample without the AlN interfacial layer ($\mu_{Hall} = 1287\ cm^2/Vs$, $\rho_s = 539$ Ω/sq., and $n_s = 0.9 \times 10^{13}/cm^2$). Electron transport properties in AlGaN/AlN/GaN structures were theoretically studied, and the calculated results indicated that the insertion of an AlN layer into the AlGaN/GaN heterointerface can significantly enhance the 2DEG mobility due to the reduction of alloy disorder scattering. HEMTs were successfully fabricated and characterized. It was confirmed that AlGaN/AlN/GaN HEMTs with the optimum AlN layer thickness show superior DC properties compared with conventional AlGaN/GaN HEMTs.

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1. Introduction

High-electron-mobility transistors (HEMTs) based on AlGaN/GaN two-dimensional-electron-gas (2DEG) structures are very promising electronic devices for use in high-temperature, high-power and high-frequency operations due to their superior material features, and HEMTs based on AlGaN/GaN structures have demonstrated outstanding performance in applications not only in high-power microwave devices [1,2] but also in high-speed switching ICs [3] or high-voltage DC–DC converters [4]. Recently, it has been reported that modified AlGaN/AlN/GaN structures, which employ a thin AlN interfacial layer between AlGaN and GaN layers, show higher 2DEG properties than those of conventional AlGaN/GaN structures [5,6]. Shen et al. reported that an AlGaN/AlN/GaN structure with a 1-nm-thick AlN interfacial layer grown on a SiC substrate showed a high room-temperature Hall mobility of 1540 cm^2/Vs with a large 2DEG density of $1.48 \times 10^{13}/cm^2$ [6]. This high performance is reported to be because the increased ΔE_C, which is defined as conduction-band discontinuity between AlGaN and GaN, effectively suppresses the electron penetration from the GaN channel into the AlGaN layer, and results in the reduction of alloy disorder scattering in AlGaN alloy [5–7]. We have also confirmed that 2DEG mobility in AlGaN/AlN/GaN structures grown by metalorganic vapor

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phase epitaxy (MOVPE) was significantly enhanced by using epitaxial AlN/sapphire templates as the underlying substrates [8]. We consider that this is due to the realization of a high-crystal-quality GaN channel by using AlN/sapphire templates. In order to realize the application of AlGaN/AlN/GaN structures to HEMTs, it is necessary to understand their basic electron transport properties as well as device characteristics. In this paper, we have investigated the effect of the thin AlN interfacial layer on the 2DEG properties in AlGaN/AlN/GaN structures using samples grown on 100-mm-diameter sapphire substrates by MOVPE. HEMTs were also fabricated using these epitaxial wafers and their DC performance was characterized.

2. Experiment

AlGaN/AlN/GaN structures with AlN interfacial layers of various thicknesses were grown on 100-mm-diameter and 630-μm-thick *c*-face sapphire substrates using a horizontal MOVPE system (Taiyo Nippon Sanso, SR-4000). Trimethylgallium (TMG), trimethylaluminum (TMA) and ammonia (NH_3) were used as Ga, Al and N sources, respectively, and monosilane (SiH_4) was used as the n-type dopant. The AlGaN layer consists of, from top to bottom, a 3-nm-thick undoped $Al_{0.26}Ga_{0.74}N$ layer, a 15-nm-thick Si-doped $Al_{0.26}Ga_{0.74}N$ layer with the doping level of approximately $5 \times 10^{18}/cm^3$ and a 7-nm-thick undoped $Al_{0.26}Ga_{0.74}N$ layer. The GaN layer thickness was maintained at 3 μm. The growth conditions of the GaN layers have been optimized to have a resistivity of higher than $1 \times 10^6\ \Omega$ cm over the entire 100-mm-diameter epitaxial wafers. The AlN interfacial layers were grown to have thicknesses of 0, 0.5, 0.75, 1.0, 1.25 and 1.5 nm according to the growth rate. The MOVPE-grown wafers were characterized by Hall effect measurement, mercury (Hg) probe capacitance–voltage (*C*–*V*) measurement and cross-sectional transmission electron microscopy (TEM).

The fabrication of HEMTs was performed using a conventional photolithographic lift-off method. Source and drain electrodes were accomplished by the evaporation of Ti/Al/Ni/Au (25/75/20/55 nm), and were subsequently annealed at a temperature of 850 °C for 30 s in nitrogen atmosphere. The gate Schottky contacts were formed by the evaporation of Pd/Ti/Au (40/20/60 nm). Device isolation was accomplished by mesa dry etching down to GaN layers by BCl_3 plasma reactive ion etching (RIE). Electron-beam-evaporated SiO_2 films were used for device passivation. The gate width (W_g) and the gate length (L_g) were 15 μm and 1.5 μm, respectively. Current–voltage (*I*–*V*) characteristics were measured using a semiconductor parameter analyzer.

3. Results and discussion

3.1. Characterization of MOVPE-grown epilayers

Fig. 1(a) and (b) show plots of Hall mobilities (μ_{Hall}) and sheet resistances (ρ_s) measured at room temperature (RT) and 77 K, respectively, for a series of samples with AlN interfacial layer thicknesses of 0, 0.5, 0.75, 1.0, 1.25 and 1.5 nm. From Fig. 1(a) and (b), it is clear that Hall mobility and sheet resistance vary with the thickness of the AlN interfacial layer, and that these have optimum values for a certain AlN layer thickness. Highly enhanced Hall mobilities with low sheet resistances, such as 1770 cm^2/Vs with 365 Ω/sq. at RT and 7260 cm^2/Vs with 87 Ω/sq. at 77 K (2DEG density $n_s = 1.0 \times 10^{13}/cm^2$), were observed for a sample with an optimum AlN layer thickness of 1.0 nm compared with those of a sample without the thin AlN interfacial layer ($\mu_{\mathrm{Hall}} = 1287\ cm^2/Vs$ at RT and 3998 cm^2/Vs at 77 K, $\rho_s = 539$ Ω/sq. at RT and 174 Ω/sq. at 77 K, $n_s = 0.9 \times 10^{13}/cm^2$).

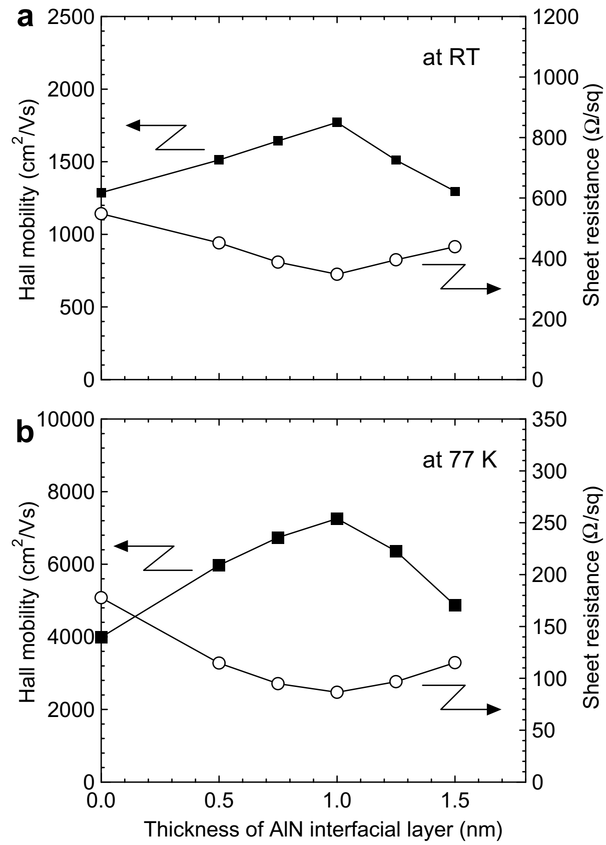

Fig. 1. Plots of mean sheet resistances and Hall mobilities measured (a) at room temperature (RT) and (b) at 77 K, respectively, for a series of AlGaN/AlN/GaN structures with AlN layer thicknesses of 0, 0.5, 0.75, 1.0, 1.25 and 1.5 nm.

Fig. 2 shows the temperature dependence of the Hall mobilities for the AlGaN/AlN/GaN structure with the 1-nm-thick AlN interfacial layer. For comparison, Fig. 2 also shows the results of the AlGaN/GaN structure. From this figure, it is clear that the saturation of Hall mobilities at low temperatures, in which the alloy disorder and/or interface roughness are the dominant scattering processes [5], is markedly reduced in the case of the AlGaN/AlN/GaN structure compared with that in the case of the AlGaN/GaN structure. This result indicates that the dominant scattering processes at low temperatures are significantly