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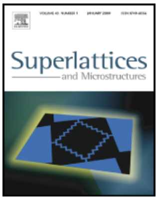

Mobility enhancement of 2DEG in MOVPE-grown AlGaN/AlN/GaN HEMT structure using vicinal (0 0 0 1) sapphire

Weiguo Hu [a,*], Bei Ma [b], Dabing Li [b,c], Mitsuhisa Narukawa [b], Hideto Miyake [b], Kazumasa Hiramatsu [b]

[a] *Venture Business Laboratory, Mie University, 1577 Kurima-machiya, Tsu 514-8507, Japan*

[b] *Department of Electrical and Electronic Engineering, Mie University, 1577 Kurima-machiya, Tsu 514-8507, Japan*

[c] *Key Laboratory of Excited State Processes, Changchun Institute of Optics, Fine Mechanics and Physics Chinese Academy of Sciences, 16 Dong Nan Hu Road, Changchun 130033, PR China*

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ABSTRACT

$Al_{0.25}Ga_{0.75}N$/AlN/GaN high electron mobility transistor (HEMT) structures were grown on (0 0 0 1) sapphire substrates with vicinal angles of 0.0°, 0.25°, 0.5° and 1.0° by metalorganic vapor phase epitaxy (MOVPE). Vicinal sapphire was demonstrated to enhance the step-flow growth to improve morphology, crystal and optical qualities, which eventually suppressed interface scattering and dislocation scattering to enhance the mobility of 2-dimension-electron-gas (2DEG). The optimum vicinal degree was determined to be 0.5°, and the corresponding 300 K Hall mobility and sheet resistance were 1720 cm^2/Vs and 301 Ω/sq, respectively. Furthermore, the temperature dependence of Hall measurements proved good high-temperature performance of the 0.5-off sample.

1. Introduction

GaN-based HEMTs have shown excellent promise in power systems, monolithic amplifiers, and wireless communications and so on [1–3]. SiC, sapphire and silicon are common foreign substrates for nitride epitaxial growth. However, due to the large lattice mismatch and thermal mismatch between substrate and nitride, the crystal quality of Al(Ga)N is still poor and the dislocation density is

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[*] Corresponding author. Tel.: +81 90 84595070.
E-mail address: huweiguo@opt.elec.mie-u.ac.jp (W. Hu).

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commonly large to 10^9–10^{12} cm^{-2}, which greatly degrades the device's performance. Recently, some groups have found that an appropriate vicinal substrate can enhance the step-flow growth to improve the GaN crystal, optical, electrical properties [4–6]. Further, Prof. Shen has proved that in the MBE-grown AlGaN/GaN HEMT structure, vicinal substrates (SiC or sapphire) are of benefit to form high-mobility 2DEG [7–9]. However, in MOVPE-growth, relative researches are very few [10], and most researchers still focus on growing simple templates rather than HEMT structures [11,12].

Additionally, a kind of modified AlGaN/AlN/GaN structure has been proved to greatly improve the 2DEG properties [13–16]. Thus, in this paper, a novel AlGaN/AlN/GaN HEMT structure was first grown on a series of vicinal sapphires with various vicinal angles of 0°, 0.25°, 0.5° and 1°. And then, we systematically investigated vicinal angle effects on the morphologies, crystal, optical and electrical properties.

2. Experimental details

AlGaN/AlN/GaN structures were grown on vicinal (0 0 0 1) sapphires by a horizontal MOVPE. Vicinal angles were 0°, 0.25°, 0.5° and 1° (the error value is less than 0.05°), and inclination direction was along the $\langle 1\ \bar{1}\ 0\ 0 \rangle$ axis. Trimethylaluminum (TMA), Trimethylgallium (TMG) and ammonia (NH_3) were used as the Al, Ga, and N precursor, respectively. Prior to growth, sapphire substrates underwent thermal cleaning for 10 min at 1100 °C in H_2 ambient, and then the chamber temperature was decreased to 500 °C to grow a 20 nm GaN nucleation layer. Next, a 2.4 μm GaN layer, a 1 nm AlN interlayer and a 22 nm $Al_{0.25}Ga_{0.75}N$ cap layer were subsequently grown at 1080 °C.

Atomic force microscopy (AFM) measurements were performed to reveal the films' morphologies. The crystal qualities were revealed by high resolution X-ray diffraction (HRXRD). The photoluminescence (PL) spectra measurements were performed at room temperature, a 213 nm laser was used as the exciting source. To perform hall measurements, a Ti/Al Ohmic contact were placed at the corners of the 1 cm × 1 cm van der Pauw samples.

3. Results and discussions

AFM images of the AlGaN/AlN/GaN structures are shown in Fig. 1. The surface of the sample grown on the on-axis substrate (hereinafter called "0.0-off sample") typically consists of small islands and random bending steps of several atomic layers in height, which implies a mixture growth model of spiral growth and step-flow growth. However, in the MBE-grown samples, the main growth model is spiral growth [7,8]. This distinct difference is attributed to the larger atomic diffusion length benefited by the higher growth temperature of MOVPE, which enhances step-flow growth to result in the mixture growth model. Further, vicinal sapphire still enhances the step-flow growth in MOVPE-grown samples: for the sample grown on a 0.25° substrate (hereinafter called "0.25-off sample"), the islands dimension decreases and the steps are gradually aligned towards the inclination direction; especially, the sample grown on a 0.5° substrate (hereinafter called "0.5-off sample") exhibits a very smooth surface, monolayer straight atomic steps, which proved that step-flow growth dominates the growth process. However, by further increasing the vicinal angle to 1.0°, the sample (hereinafter called "1.0-off sample") exhibits large macrosteps and very rough morphology, which indicates the presence of step-bunching. It shows that too large a vicinal angle fails to maintain the monolayer step-flow growth under the present growth conditions. Interface scattering is one important scattering process, and surface morphology partly reveals the interface property of the HEMT structure [16]. Thus, the smoothest sample, the 0.5-off sample, is expected to inhibit interface scattering to enhance 2DEG mobility.

Dislocation scattering is another important scattering process. The main dislocation types include screw-dislocation, edge-dislocation and mixture-dislocation, which broaden the HRXRD rocking curves of the (0 0 0 4), $(1\ 0\ \bar{1}\ 0)$ and $(1\ 0\ \bar{1}\ 2)$ planes, respectively. Fig. 2(a) exhibits the FWHM values of GaN rocking curves. Compared with the 0.0-off sample, the 0.25-off sample and the 0.5-off sample exhibit prominent decreases in screw-, edge-dislocations and mixture-dislocations; however, the GaN crystal qualities of the 1.0-off sample possess overall degradation. Similar results are also been

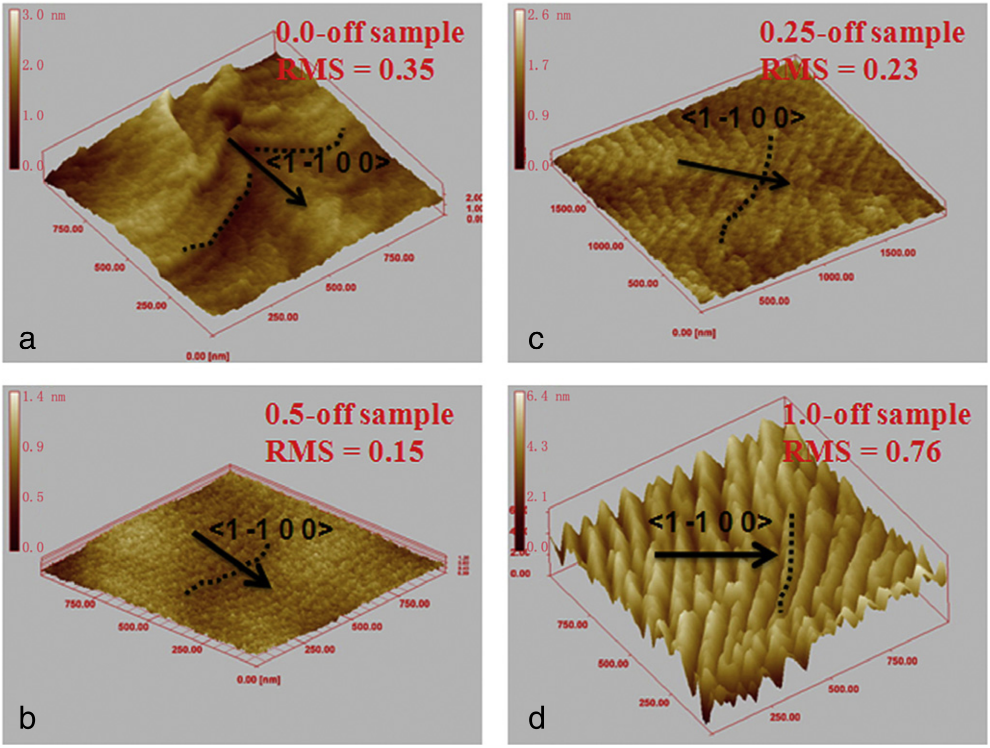

Fig. 1. AFM images of AlGaN/AlN/GaN HEMT structure grown on the (0 0 0 1) sapphire substrate with different vicinal angles: (a) 0.0° (on-axis substrate), RMS = 0.35 nm, (b) 0.25°, RMS = 0.23 nm, (c) 0.5°, RMS = 0.15 nm, and (d) 1.0°, RMS = 0.76 nm.

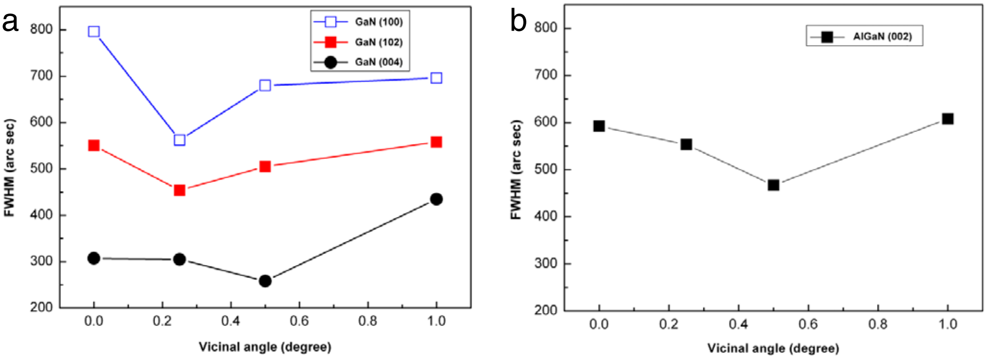

Fig. 2. (a) Vicinal angle dependence of the FWHM of GaN (0 0 0 4), (1 0 $\bar{1}$ 0) and (1 0 $\bar{1}$ 2) diffraction evaluated by HRXRD omega-scans. (b) Vicinal angle dependence of the FWHM of AlGaN (0 0 0 2) diffraction evaluated by HRXRD omega-scans.

observed in AlGaN cap layers (see Fig. 2(b)). The improvements in GaN and AlGaN crystal qualities seem to be caused by misorientation which relieves the lattice mismatch between the GaN and sapphire [10] and enhances step-flow growth [11].

Fig. 3(a) shows the room temperature PL spectra of AlGaN/AlN/GaN HEMT structures on different vicinal sapphire (0 0 0 1) substrates. All of the PL spectra exhibit two main peaks: one is related to GaN band-edge emission, at 3.42 eV; another is related to AlGaN band-edge emission, about 3.90±0.02 eV. The slight shift of the AlGaN band-edge emission peaks is attributed to a non-uniform Al-content or

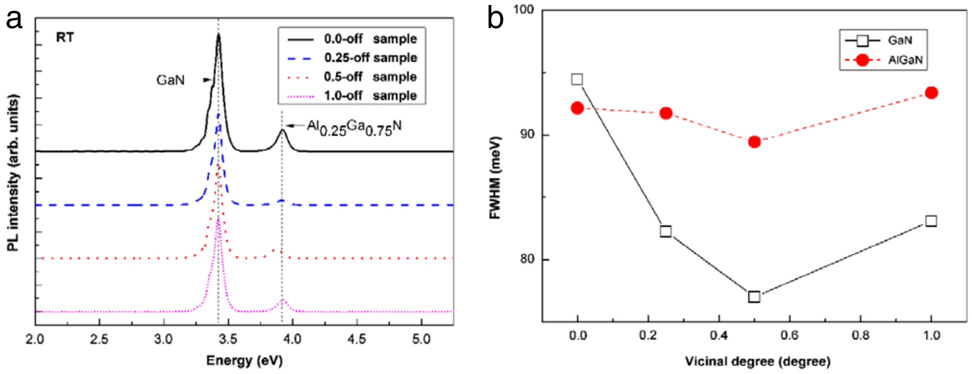

Fig. 3. (a) PL spectra of AlGaN/AlN/GaN HEMT structures grown on different vicinal sapphire (0 0 0 1) substrates at room temperature. (b) The dependence of FWHM of GaN and AlGaN band-edge emission on the vicinal angle.

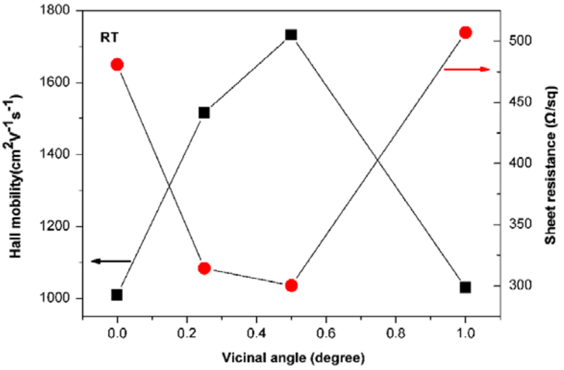

Fig. 4. Dependence of the Hall mobility and sheet resistance in AlGaN/AlN/GaN HEMT structures grown on the vicinal angle at 300 K.

in-plane stress. No clear yellow peaks are observed in the PL spectra, which means high crystal quality, especially low Ga-vacancy density. Fig. 3(b) exhibits the dependence of GaN and AlGaN band-edge emission FWHM values on the vicinal angle. From the figure, it is clear that the FWHM values of the GaN- and AlGaN-related emission peaks decrease with the vicinal angle increasing to 0.5°; however, a further increase to 1.0° degrades their optical property increases instead.

Fig. 4 exhibits the results of the Hall measurements at 300 K. From Fig. 4, we found that the Hall mobility and sheet resistance show dramatic improvements by increasing the vicinal angle to 0.5°. The 0.5-off sample has the highest Hall mobility and lowest sheet resistance at 300 K, 1720 cm^2/Vs and 301 Ω/sq, respectively. The electrical property enhancement is consistent with film-quality improvements (including flat surface morphology, low dislocation density and narrow PL spectra). Especially, the 1.0-off sample fails to exhibit better electrical qualities than the 0.0-off sample. It is very different with MBE-grown GaN-based HEMT whose mobility monotonously increased with increasing vicinal angle from 0.0° to 2.0° [7–9]. A possible reason is that due to the high atomic diffusion length in MOVPE-growth, step-bunching emerges earlier in a vicinal substrate (1.0°), which greatly degrades the morphologies to enhance interface scattering.

The temperature dependence of Hall mobility was revealed in Fig. 5(a). At the range from 78 K to 450 K, the Hall mobility of the 0.25-off sample and the 0.5-off sample are far higher than those of the 0.0-off sample and the 1.0-off sample. Especially, at this temperature range, the 0.25-off sample exhibits a very high Hall mobility, 19 020 cm^2/Vs at 78 K. By further decreasing the temperature, this value should increase further. Additionally, at the low temperature range from 78 K to 172 K,

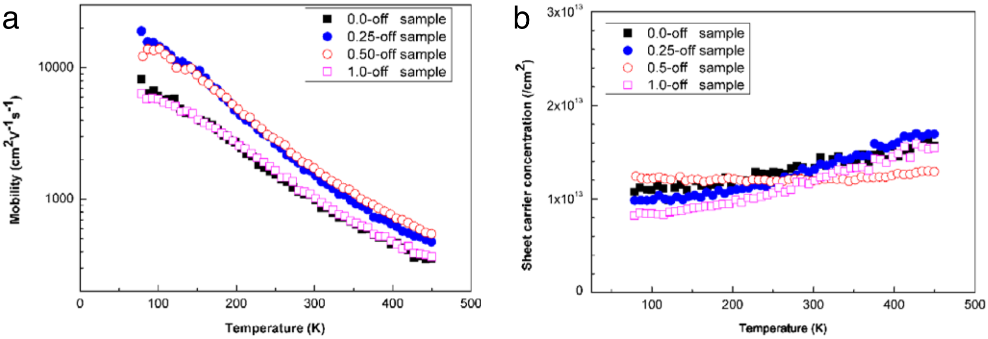

Fig. 5. The vicinal angle dependence of the electrical properties at temperatures of 78–450 K evaluated by VDP Hall measurements. (a) Temperature dependence of the mobility. (b) Temperature dependence of the sheet carrier density.

the mobility of the 0.25-off sample is slightly higher than that of the 0.5-off sample; contrarily, at temperatures from 180 K to 450 K, the 0.5-off sample exhibits higher mobility than the 0.25-off sample. An important application of GaN-based HEMT is as a high-temperature and high-power electronic device. Thus, the 0.5-off sample is more appropriate for high-power HEMT fabrication. Fig. 5(b) shows the temperature dependence of the sheet carrier densities. The sheet carrier densities of the 0.0-off, the 0.25-off and the 1.0-off samples slightly increase at 200 K–450 K range, which suggests an involvement of an additional 3D conductivity channel; by contrast, that of the 0.5-off sample is almost independent of temperature, a typical feature of 2DEG. The elimination of the 3D conductivity channel in the 0.5-off sample should be a secondary factor for Hall mobility improvement.

4. Conclusion

In conclusion, we present a systemic study of vicinal (0 0 0 1) sapphire effects on the MOVPE-grown AlGaN/AlN/GaN HEMT structure. Vicinal sapphire substrates were demonstrated to enhance step-flow growth. Changes of the growth model greatly affected the morphology, crystal, and optical qualities, which eventually resulted in a strong dependence of mobility and sheet resistance on vicinal angles. Different with monotonously increasing mobility in MBE growth (0.0°–2.0°) [7–9], a slight vicinal sapphire is of benefit to form high quality 2DEG, and the optimum vicinal angle in our MOVPE-growth was determined to be 0.5°. Additionally, the 0.5-off sample also exhibits good high-temperature performance. Thus, the appropriate vicinal substrate usage shows the promise of great potential for high quality GaN-based HEMT fabrication by MOVPE.

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