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Strained Thick p-InGaN Layers for GaN/InGaN Heterojunction Bipolar Transistors on Sapphire Substrates

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1. Introduction

Nitride electronic devices have attracted much attention because they have a high potential for high-power applications. On the other hand, among electronic transistors, the heterojunction bipolar transistor (HBT) has several advantages, such as high current density, high breakdown voltage, good linearity, low phase noise, and good threshold voltage uniformity. Therefore, nitride HBTs are preferable as the high-power electronic devices for high-quality communications systems. Recently, we have reported an AlGaN/InGaN HBT that shows high breakdown voltage of over 120 V with a corresponding electric field as high as 2.3 MV/cm, [1] which is much higher than those reported for HBTs composed of other materials, such as Si/SiGe, InGaP/GaAs and InP/InGaAs. However, reported nitride HBTs have a relatively small current gain and a high offset voltage of around 5 V in the common-emitter current-voltage (I-V) characteristics because of the degraded ohmic characteristics of the base of nitride HBTs. Recently, we improved the ohmic characteristics using the regrowth of the p-InGaN base and successfully fabricated Npn-type GaN/InGaN HBTs with a high current gain and a low offset voltage on SiC substrates [2]. In these HBTs, the thickness and the In mole fraction of the p-InGaN base were 100 nm and 7 %, respectively. The thickness of the p-InGaN base on the GaN collector exceeded the calculated critical thickness (less than 10 nm) [3], so it is important to investigate the strain of such relatively thick p-InGaN on GaN. Furthermore, there are no reports on high current gains and low offset voltages for nitride HBTs on sapphire substrates. The characteristics of HBTs on sapphire substrates are worth investigating because sapphire substrates are cheaper than SiC substrates. In this conference, we report on the strain of p-InGaN layers as well as the characteristics of GaN/InGaN HBTs on sapphire substrates.

2. Experimental Procedures

The p-InGaN/undoped GaN structures were grown on sapphire substrates by metalorganic vapor phase epitaxy using the conventional two-step growth technique. The growth temperatures of the undoped GaN and p-InGaN layers were 1000 °C and 780 °C, respectively. The thicknesses of the undoped GaN and p-InGaN layers were 1 μm and 180 nm, respectively. The In mole fraction of p-InGaN was changed from 1.6 % to 11 % to analyze the strain inside the p-InGaN layer by reciprocal space map of the X-ray diffraction intensity.

We fabricated GaN/InGaN HBTs on sapphire substrates using a p-InGaN base. The collector is 500-nm n-GaN with a Si doping concentration of 1×10^{17} cm^{-3}. The base is 100-nm p-InGaN with a Mg doping concentration of 1×10^{19} cm^{-3}. The corresponding hole concentration was 2×10^{18} cm^{-3} at room temperature. The Si doping concentration of the n-GaN emitter layer was 4×10^{19} cm^{-3}, since ohmic characteristics of the emitter were not obtained for lower Si doping concentrations because Mg atoms in the base diffuse into the emitter to compensate Si donors. The p-InGaN extrinsic base was regrown at 750 °C to avoid the influence of the etching damage for the base [4].

3. Experimental Results

Figure 1 shows a typical reciprocal space map of the X-ray diffraction intensity for p-InGaN with an In mole fraction of 7 %. There are two peaks in Fig. 1. One peak

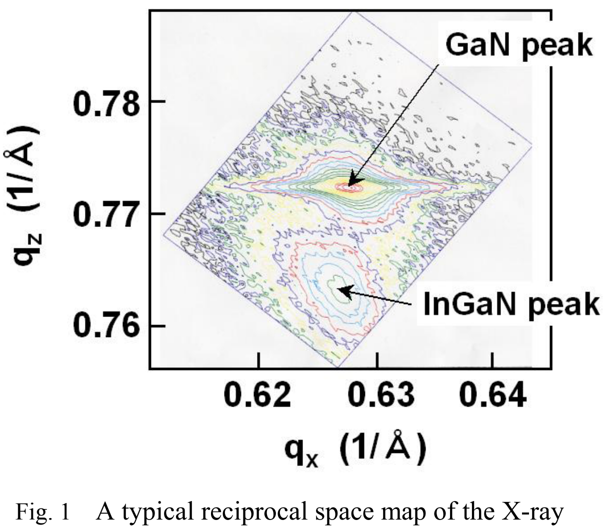

Fig. 1 A typical reciprocal space map of the X-ray diffraction intensity for p-InGaN with an In mole fraction of 7 %

corresponds to the undoped GaN, and the other to p-InGaN. This result means that the phase separation of InGaN was negligibly small in this experiment. The two peaks have a similar x-axis position, meaning that the p-InGaN layer is strained in spite of its 180-nm thickness. It has been reported that 40-nm InGaN on GaN with an In mole fraction of 15 % is fully strained [5], so our experimental result shows that the strain remained even for thicker InGaN layers.

From the X-ray diffraction analysis, the a-axis and c-axis lattice constants were obtained for p-InGaN. Using these lattice constants, we determined the In mole fraction of p-InGaN. To investigate the strain inside thick p-InGaN quantitatively, we define the "strain-rate" as follows:

$$[\text{strain-rate}] = [\, a(\text{InGaN}) - a(x)\,] / [\, a(\text{InGaN}) - a(\text{GaN})\,]$$

where a(x) and a(GaN) are experimentally obtained a-axis lattice constants of p-InGaN and undoped GaN, respectively. The symbol a(InGaN) is an a-axis lattice constant for fully relaxed p-InGaN. In the above equation, the strain-rate is unity for the fully strained p-InGaN, where a(x) is equal to a(GaN). On the other hand, it is zero for the fully relaxed p-InGaN, where a(x) is equal to a(InGaN).

Figure 2 shows the strain-rate as a function of the In mole fraction of p-InGaN. Even though the calculated critical thickness is less than 10 nm for p-InGaN with an In mole fraction of 10 %, the 180-nm p-InGaN layers were considerably strained. This means that a large part of the p-InGaN grew coherently on the GaN and that few dislocations were generated at the InGaN/GaN interface in spite of the relatively large lattice mismatch.

Using this strained thick p-InGaN as a base, we fabricated a GaN/InGaN HBT on a sapphire substrate. Figure 3 shows its common-emitter I-V characteristics at room temperature. Its emitter size is 50 μm x 30 μm. The maximum current gain was as high as 1000 and the offset voltage as low as 0.5 V. We have reported that the dislocations decrease the minority carrier diffusion length, that is, the current gain of the HBTs [6]. Therefore, this high HBT performance was obtained because fewer dislocations were generated at the InGaN/GaN interface in the GaN/InGaN HBT.

4. Conclusions

We grew thick p-InGaN layers on GaN and the strain inside the p-InGaN was qualitatively analyzed by reciprocal space map of the X-ray diffraction intensity. It was found that a large part of the p-InGaN grew coherently on the GaN and that few dislocations were generated at the InGaN/GaN interface in spite of their relatively large lattice mismatch. Using this strained thick p-InGaN as a base, we fabricated a GaN/InGaN HBT on a sapphire substrate. The maximum current gain was as high as 1000 and the offset voltage as low as 0.5 V. This high performance was achieved because fewer dislocations were generated at the InGaN/GaN interface in the GaN/InGaN HBT on a sapphire substrate.

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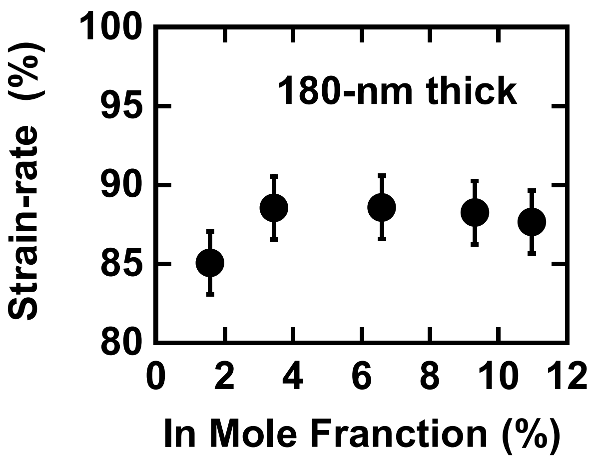

Fig. 2 Strain-rate as a function of In mole fraction of p-InGaN.

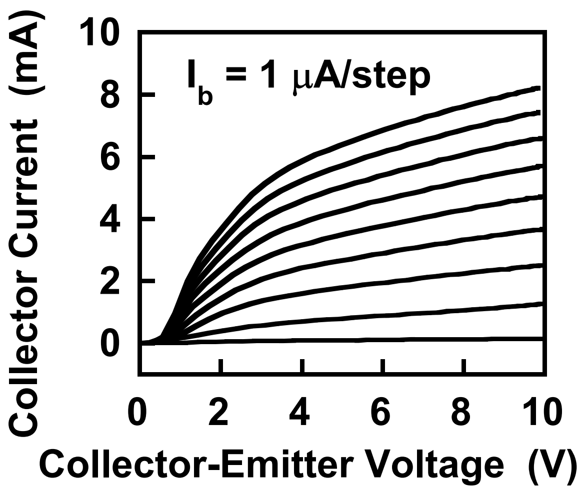

Fig. 3 Common-emitter I-V characteristics of the GaN/InGaN HBT on sapphire substrate.