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Gallium-nitride-based Heterojunction Bipolar Transistors with Two-dimensional Hole Gas Fabricated by Epitaxial Lift-off Process

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Abstract

We investigated gallium nitride (GaN)-based *npn* emitter top-structure heterojunction bipolar transistors (HBTs) applying two-dimensional hole gas (2DHG). The structure was grown on a free-standing GaN substrate by metalorganic vapor phase epitaxy (MOVPE), and fabricated by the epitaxial lift-off (ELO) process involving selective photoassisted electrochemical etching of indium gallium nitride (InGaN). A maximum DC current gain of ~3 was achieved with an emitter diameter of 40 µm, as determined from a Gummel plot measured at room temperature.

1. Introduction

Gallium nitride (GaN)-based heterojunction bipolar transistors (HBTs) are promising devices for application in high-frequency communication and switching. HBTs have better linearity, threshold voltage and higher current density than field-effect transistors (FETs). However, in the case of group-III nitride semiconductors, the acceptor activation energy in the Mg-doped *p*-type GaN base layer is as high as 112 to 190 meV, and its activation efficiency is about 1% at room temperature [1-2]. This leads to an increase in the base resistance and limits the high-frequency operation or current density. In order to resolve this, we focused on two-dimensional hole gas (2DHG) induced by negative polarization at the heterointerface between GaN and aluminum gallium nitride (AlGaN).

Recently, it has been reported that 2DHG with a high sheet hole density of 1.1×10^{13} cm^{-2} (over 10^{19} cm^{-3} estimated) was obtained at a GaN/AlGaN interface [3]. Our group has also reported a reduction in the sheet resistance of *p*-GaN upon the introduction of 2DHG [4]. In addition, we have fabricated and characterized *npn* collector top-structure HBTs with 2DHG in the base layer [4]. In the experiment, the obtained current gain was only 0.003. As a possible reason, we assume that electrons injected from the emitter easily recombined with holes from the base since the emitter electrode was directly below the base electrode in the collector-top structure in which the emitter is larger than the collector. This problem was resolved by fabricating the emitter top-structure on the N-face (-c plane) to prevent recombination under the base electrode. However, it was difficult to grow GaN on N-face GaN owing to the unintentional incorporation of impurities. As the solution, an epitaxial lift-off (ELO) process was employed to fabricate emitter top-structure HBTs. In this paper, we report the novel fabrication process and marked improvement in the DC current gain.

2. Experiments

The structure was grown on a Si-doped *n*-type free-standing GaN (FS-GaN) substrate by metalorganic vapor phase epitaxy (MOVPE) under a pressure of 500 hPa. From the substrate up, the device structure consists of 500-nm-thick Si-doped n^+-GaN ([Si]: 1×10^{18} cm^{-3}), 100 nm unintentionally doped (UID) indium gallium nitride (InGaN) release layer,

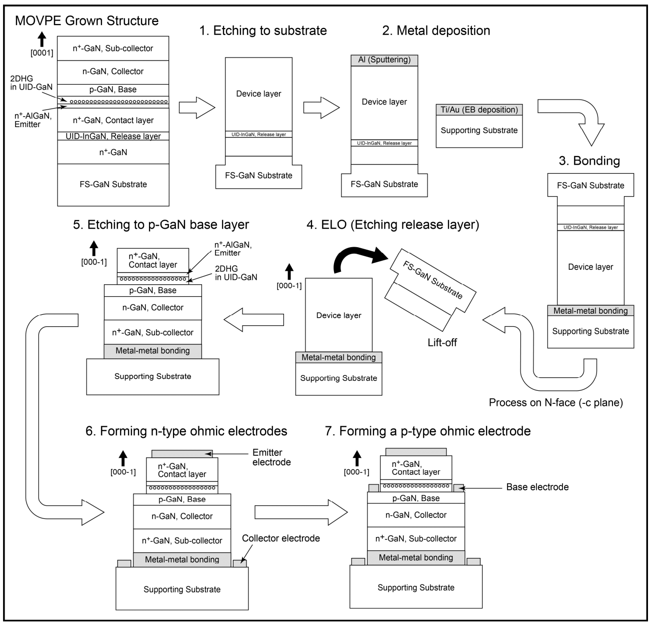

Fig. 1 Schematic of fabrication procedure.

500 nm n^+-GaN ([Si]: 1×10^{18} cm^{-3}) contact layer, 50 nm n^+-AlGaN ([Si]: 1×10^{19} cm^{-3}) emitter, 100 nm UID-GaN, 150 nm Mg-doped p-GaN ([Mg]: 8×10^{18} cm^{-3}) base, 500 nm n-GaN ([Si]: 8×10^{16} cm^{-3}) collector, and 500 nm n^+-GaN sub-collector ([Si]: 1×10^{18} cm^{-3}).

The process flow for device fabrication is shown in Fig. 1. First, a mesa was formed by Cl_2 inductive coupled plasma–reactive ion etching (ICP–RIE) to expose the InGaN release layer for the ELO process. Second, Al was deposited by sputtering on the mesa for bonding process. In addition, we prepared another FS-GaN substrate on which to transfer the epitaxial device layer or to support it after the ELO process, and deposited Ti/Au by electron-beam (EB) evaporation. Third, metal-metal bonds were formed between them by rapid thermal annealing (RTA) at 700°C for 1 h. Fourth, ELO was accomplished by the selective photoassisted electrochemical (PEC) etching of the InGaN release layer in KOH aq. (1 mol/L, 1 h after 0.3 mol/L, 30 min) with light irradiation ($\lambda >$ 365nm). Fifth, the emitter mesa was formed by Cl_2 ICP–RIE to expose and form an electrical contact with the p-GaN base layer. Finally, a Ni/Au p-type ohmic contact for the base electrode, and a Ti/Al/Ti/Au n-type ohmic contact for collector and emitter electrodes were deposited by EB evaporation. In this process, electrodes were alloyed at 525°C for the base and 650°C for the collector and emitter by RTA.

3. Result and Discussion

Fig. 2 shows a Gummel plot of fabricated HBTs, measured at room temperature. A maximum DC current gain of ~3 was achieved with a 40-μm-diameter emitter mesa. This is about 1000 times larger than that of the collector top-structure and the first report of one on a GaN-based HBT with the capability of current amplification, fabricated by the ELO process. We also investigated the I–V characteristics of two terminals; base-collector (B-C), base-emitter (B-E), and collector-emitter (C-E). From Fig. 3, the ideality factor n of the B-C and the B-E pn diodes are found to be about 8.61. Since the value of n exceeds 2 when series or shunt resistances of di odes become dominant in the I–V characteristics, it is indicated that these resistances are high in the fabricated HBTs. As a possible reason, we speculate that the net acceptor concentration of the p-GaN surface decreased owing to the plasma of ICP–RIE used to expose the base layer. This phenomenon made the contact resistance of p-GaN higher than that of the as-grown surface [5].

These results demonstrate the validity of the fabricated structure and the ELO process with respect to GaN-based HBTs, and indicate the possibility of obtaining higher current gain by optimizing the etching conditions of N-face p-GaN to reduce the base contact resistance.

4. Conclusions

We fabricated GaN-based HBTs by the ELO process. For the first time, a maximum DC current gain of ~3 was achieved with emitter diameter of 40 μm as determined from the Gummel plot measured at room temperature. I–V characteristics of two terminals were also investigated. From the results, we inferred that it is possible to obtain higher current gain by optimizing the etching conditions for N-face p-GaN to reduce the base contact resistance.

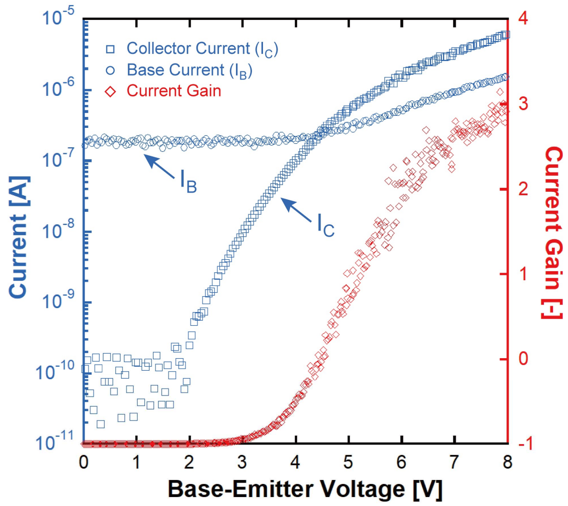

Fig. 2 Gummel plot of a fabricated HBT (emitter mesa diameter: 40 μm, @ R.T.).

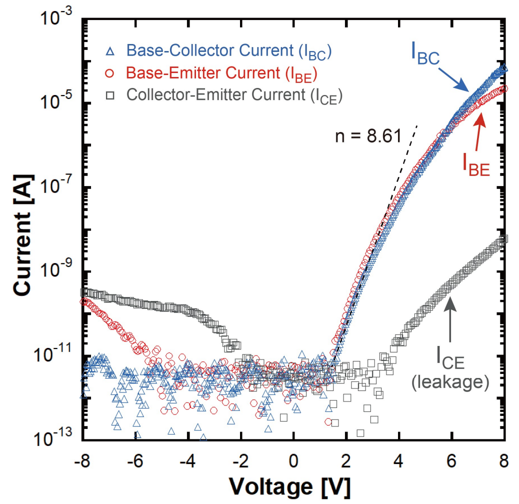

Fig. 3 I–V characteristics of two terminals between base and collector, base and emitter, and collector and emitter (@ R.T.).

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