Extended Abstracts of the 2000 International Conference on Solid State Devices and Materials, Sendai, 2000, pp. 152–153

LE-1-1

Very-Large-Gain Collector-Up $GaN/W/WO_3$ Metal Base Transistors

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1. Introduction

Among GaN-based electronic devices, AlGaN/GaN high electron mobility transistors (HEMTs) have already demonstrated record figures for high power microwave performance [1]. AlGaN/GaN heterojunction bipolar transistors (HBTs) are now being extensively studied [2] because of such advantages as normally off characteristics and low phase noise properties expected from a bulk device. However, their base resistance is very high due to the difficulty in achieving a high hole concentration and mobility.

The metal base transistor (MBT), which uses low-resistivity metal as a base, should greatly improve the rf performance while maintaining the advantages of HBTs. So far, MBTs with high common-emitter current gain β and common-base current gain α have been demonstrated in several material systems: $\beta = 100$ in Si/Mo/Si [3], $\beta = 1.4$ in GaAs/W/GaAs [4], $\alpha = 0.95$ in $Si/CoSi_2/Si$ [5], and $\alpha = 0.8$ in GaAs/Nb/InSb [6]. To the authors' knowledge, however, there have been no reports on GaN–based MBTs. Nitride semiconductors provide very large Schottky barrier heights, which offer the opportunity for launching electrons with particularly high energy into metal layers. In this letter, we report an MBT consisting of GaN emitter, W base, and W-oxide collector in collector-up configuration. Very high β and dc power gain were attained through ultra-thin base formed after selective oxidation of the W.

2. Device Fabrication

Schematic cross-section of the fabricated MBT is shown in Fig. 1. The MBT had a Au/Pt/Ti Schottky collector contact area of 30 x 30 μm^2, a W-oxide/W base-collector junction area of 40 x 40 μm^2. First, a 1.0-μm-thick GaN sub-emitter layer (Si: 1 x 10^{18} cm^{-3}) and a 0.50-μm-thick GaN emitter layer (Si: 5 x 10^{16} cm^{-3}) were grown by metal-organic chemical vapor deposition on a *C*-plane sapphire substrate. Subsequently, a 4.5-nm-thick W film was deposited on the GaN emitter layer by RF sputtering. This was followed by deposition of a SiO_2 film using plasma-enhanced chemical vapor deposition (PECVD) at 300°C and by formation of SiO_2 opening using photolithography and wet chemical etching. The sample was then mounted on a Mo holder with In solder and was transferred to molecular beam epitaxy chamber for selective oxidation of the W at 500°C for 2 min under ultra-high vacuum (1 x 10^{-8} Pa). After removing the SiO_2 using wet chemical etching, we observed the color of surface using optical microscopy and confirmed that while negligible oxidation occurred in the area where the SiO_2 covered, severe oxidation of the W took place in the collector area. Auger electron spectroscopy and X-ray photoelectron spectroscopy revealed that about half the thickness of the initial W film was oxidized and became WO_3.

Next, a SiO_2 film was deposited on the selectively oxidized W film by PECVD at 300°C. This was followed by base mesa photolithography, wet chemical etching of the SiO_2, and reactive ion etching (RIE) of the W. After removing the photoresist, the GaN emitter and 0.15-μm-thick GaN sub-emitter were etched by RIE using the SiO_2 as a mask. The SiO_2 mask was then removed by wet chemical etching, and an Al/Ti emitter electrode was formed on the GaN sub-emitter surface by a liftoff technique followed by alloying at 650°C for 40 sec. Finally, a Au/Pt/Ti electrode was formed by a liftoff technique on the W-oxide as a Schottky collector contact, and on the W base and the Al/Ti emitter electrodes as probing pads.

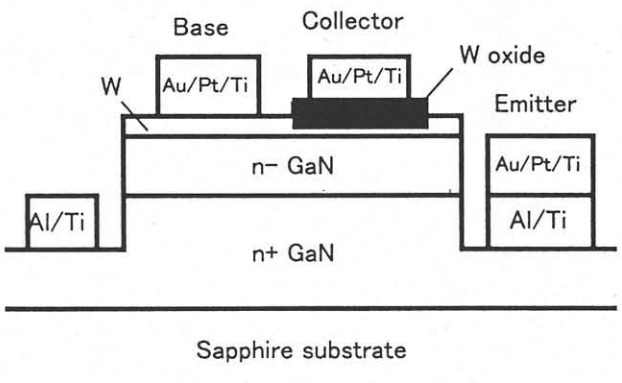

Fig. 1. Schematic illustration of cross-section of the fabricated collector-up metal base transistor.

3. Device performance

Figure 2(a) shows the common-emitter current-voltage characteristics measured at room temperature using an HP 4155 curvetracer. The large collector leakage with a turn-on voltage of 0.4 V indicates that the Au/Pt/Ti collector electrode touched the n-GaN emitter through pores in the W base [4]. Careful control of the W

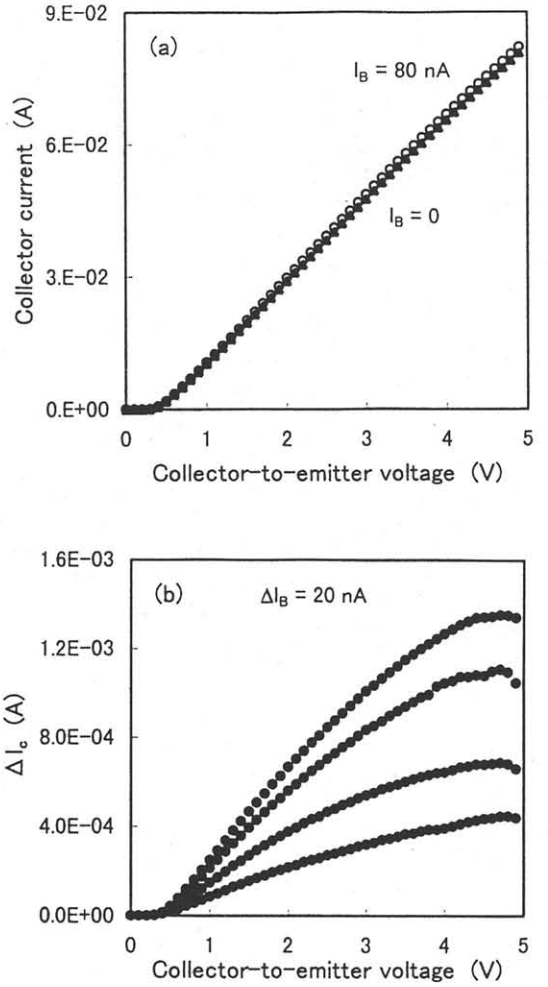

Fig.2. (a) Common-emitter current-voltage characteristics with base currents of 80 nA and 0. (b) Collector-to-emitter voltage dependence of ΔI_C which is defined as $I_C(I_B) - I_C(I_B = 0)$.

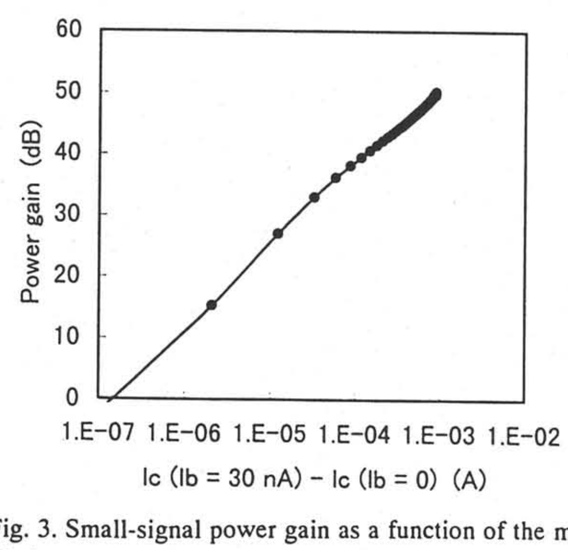

Fig. 3. Small-signal power gain as a function of the mean ΔI_C between $\Delta I_C(I_B = 20$ nA) and $\Delta I_C(I_B = 40$ nA).

deposition condition is expected to decrease the collector leakage. Here we define the modulated output current ΔI_C as the difference between the collector current I_C at a certain base current I_B and the I_C at $I_B = 0$. Figure 2(b) shows the collector-to-emitter voltage (V_{CE}) dependence of the ΔI_C with I_B from 20 to 80 nA (20 nA step). When $I_B \geqq 100$ nA, ΔI_C did not increase from the results with I_B = 80 nA. We have not yet understood what caused the ΔI_C saturation. The peak β reached 2.2 x 10^4 (87 dB) at V_{CE} = 4.7 V when I_B = 20 to 40 nA. This β almost agrees with the observed α = 0.99995 in common-base current-voltage characteristics. The dc power gain was calculated from the curves of I_B = 20 and 40 nA in Fig. 2(b) with the obtained base-emitter voltage, and the result is shown in Fig. 3 as a function of the mean ΔI_C between ΔI_C (I_B = 20 nA) and ΔI_C (I_B = 40 nA). The maximum dc power gain of 50 dB was achieved at ΔI_C = 0.90 mA. The detailed mechanisms of current flow leading to the very high β are not yet fully understood; however, the large incremental power gain unequivocally confirms transistor operation.

No ac measurements of the device characteristics have been made. It is likely that the device has the potential for very high cut-off frequency (f_T), as a result of the ultrashort dimensions involved. Although the maximum oscillation frequency (f_{max}) may be limited due to large base-collector capacitance in the present implementation, very high f_{max} can be expected by increasing the thickness of the W oxide, particularly because of the potentially low resistance of the metal base.

4. Conclusions

The fabricated collector-up GaN/W/WO_3 metal base transistor on a sapphire substrate showed a very large small-signal dc current gain of 87 dB and a dc power gain of 50 dB. These results indicate that the GaN-based MBT is a possible candidate for microwave and millimeterwave amplifiers as well as for high-speed IC's used in optical fiber communication system.

Acknowledgements

The authors would like to thank Mr. D. Qiao of Department of ECE Dept., University of California, San Diego, for his support for making ohmic contacts to GaN.

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