A Novel AlGaN/GaN Field-Effect Diode with a Low Turn-on Voltage Operation using Fluoride-Based Plasma Treatment

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Abstract

The fabrication and I-V characteristics of the novel AlGaN/GaN field effect diode are reported. This diode has a distinguishing anode structure and the relatively thick AlGaN barrier layer in contrast a conventional field-effect Schottky barrier diode (FESBD). By using fluoride-based plasma treatment, we could reduce its turn-on voltage to 0 V and decrease its leakage current at the reverse voltages.

INTRODUCTION

Nitride semiconductors, such as GaN, are promising materials for high-temperature, high-frequency, and high-power electronic device applications because of their excellent features. Recently, as a kind of the GaN-based device, the FESBD [1, 2] has been presented.

Here we report a novel AlGaN/GaN field-effect diode. The FESBD in [1] and [2] has a 5 nm-thick barrier layer and the anode comprised of a metal having a low Schottky barrier enfolded in a metal having a high Schottky barrier. In contrast, our field-effect diode has a 30 nm-thick AlGaN barrier layer and the anode consisted of Schottky and ohmic electrodes combination. We named it Schottky-ohmic combined anode field-effect diode (SOCFED) due to its distinguishing anode structure. In the SOCFED, the turn-on voltage is reduced to 0 V and the leakage current at the reverse voltages is decreased, which is achieved by a treatment of fluoride-based plasma exposure to the surface of the AlGaN barrier layer underneath the Schottky electrode.

FABRICATION OF SOCFED

Fig. 1 shows a schematic cross-section drawing of the fabricated SOCFED. The epitaxial layers were grown on a high-resistivity Si substrate. The layers consist of a GaN-based buffer layer, a 1 μm-thick i-GaN layer, and an undoped AlGaN barrier layer. The Al content of the barrier layer was 25%. In the as-grown state, the sheet resistance of this wafer was 480 Ω/□ and the sheet carrier density of the 2DEG was 7×10^{12} /cm^2. The ohmic electrode 1 and 2 were composed of Hf/Al/Hf/Au, and the Schottky electrode consisted of WN-based materials. The ohmic electrode 1 and the Schottky electrode were combined as the anode. The length between the anode and the cathode was 5 μm.

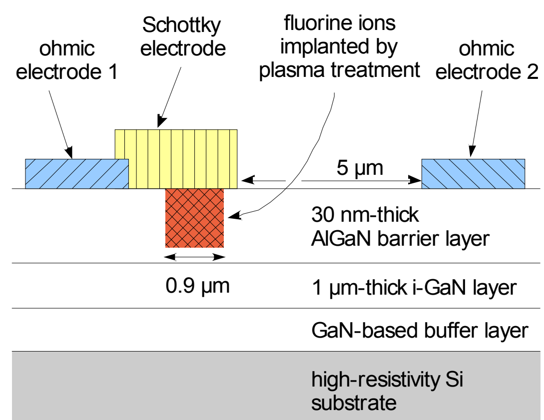

Fig. 1 Schematic cross-section drawing of the SOCFED.

The thickness of the AlGaN barrier layer in the FESBD in [1] and [2] is 5 nm, so that the current channel provided by the 2DEG underneath the Schottky electrode can be depleted at the bias voltage of 0 V. However, it has been pointed out that both the mobility and the 2DEG are reduced by decreasing the thickness of the AlGaN barrier layer [3]. Furthermore, a thinner AlGaN barrier layer, as used in the FESBD, makes it difficult to protect the AlGaN/GaN interface completely from some process damages, such as sputtering and plasma CVD methods.

To avoid these problems, we used the fluoride-based plasma treatment [4-6] for the relatively thick AlGaN barrier layer, which enabled us to deplete the 2DEG in the current channel underneath the Schottky electrode. In our SOCFED, the thickness of the AlGaN barrier was set to 30 nm. Prior to the Schottky electrode formation, the plasma treatment was applied in the way that a portion of the Schottky electrode's footprint on the AlGaN surface was exposed to the fluoride-based plasma, as shown in Fig. 1, with a parallel-plate type RIE system. The length of the exposed region was 0.9 μm. After the plasma treatment, thermal treatment for removing the plasma damages was applied. The fluoride-based plasma was excited from CF_4-based gas under the pressure of 5 Pa. The parameters of exposure treatment were the input RF power for exciting the plasma and the exposure time.

EXAMINATION OF THE FLUORIDE-BASED PLASMA TREATMENT

Fig. 2 shows the variation of the I-V characteristics of the SOCFED with the fluoride-based plasma exposure time. The input RF power of the RIE system is constant at 250 W.

When the exposure time is short, the large leakage current at the reverse voltages flows because the current channel underneath the Schottky electrode is not completely depleted. When the exposure time is long, on the other hand, the on-resistance increases, which probably causes by the negative influence of the fluoride-based plasma exposure to the current channel.

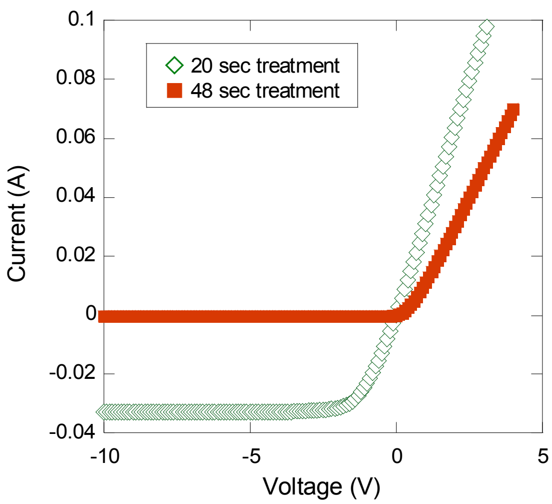

Fig. 2 Variation in the I-V characteristics of the SOCFED with fluoride-based plasma exposure time.

To suppress both the current leakage and the on-resistance increase, we optimized the condition of the fluoride-based plasma treatment. For this purpose, the effect of the treatment was examined by using FATFETs whose epitaxial layer structure was the same as the SOCFED's. The fluoride-based plasma treatment was applied to the portion of the gate's footprint on the AlGaN surface, in the same way as the SOCFED.

Fig. 3 and 4 show the I_d-V_g and transconductance (g_m)-V_g characteristics of the FATFETs. In this case, the input RF power of the RIE system is the variable parameter and the exposure time is constant at 60 s. For reference, the V_{th} without the fluoride-based plasma treatment is -4 V. As the input RF power increases, the V_{th} shifts to the positive direction. This is because the 2DEG of the current channel underneath the gate is decreased by fluorine ions implanted into the AlGaN barrier layer [4]. On the other hand, the g_m tends to decrease with the shift of V_{th}.

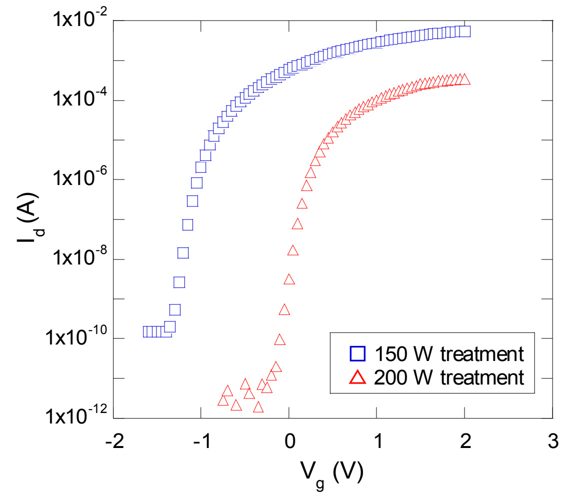

Fig. 3 I_d-V_g characteristics of FATFETs with the fluoride-based plasma treatment.

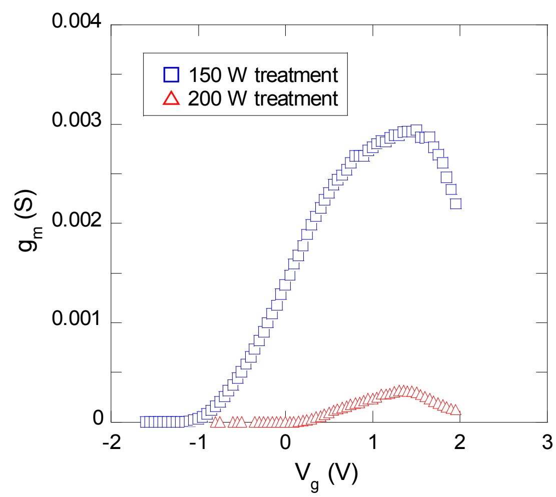

Fig. 4 g_m-V_g characteristics of FATFETs with the fluoride-based plasma treatment.

Fig. 5 shows the relation between the mobility of the current channel and the self-bias voltage related to the etching power of the RIE. Obviously in Fig. 5, the mobility of the current channel decreases as the self-bias voltage increases, suggesting that the high-power plasma treatment causes degradation of the g_m.

According to the above-mentioned fact, it seems to be preferable that lower self-bias voltage be used to suppress the on-resistance increase in the SOCFED. However, we found that, after the thermal treatment for removing the plasma damages, the shift of the V_{th} was not enough in the self-bias voltage condition of less than 400 V. The insufficient V_{th} shift implies the insufficient depletion of the 2DEG underneath the Schottky electrode in the SOCFED, so that the current leakage at the reverse voltages increases. Therefore, we decided that the self-bias voltages higher than

500 V were used as the condition for fluoride-based plasma treatment.

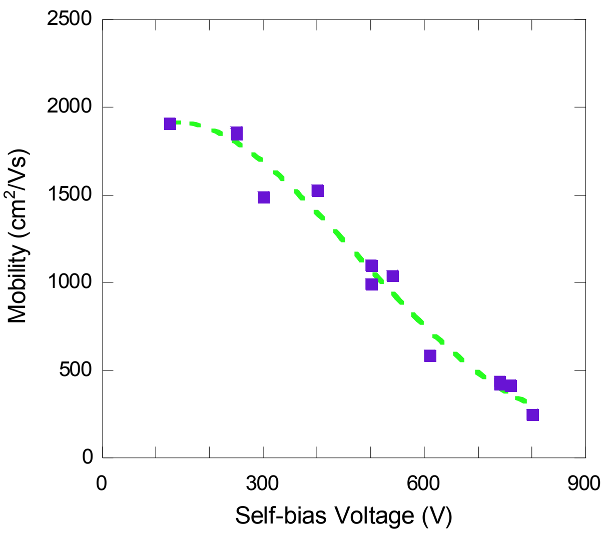

Fig. 5 Relation between the mobility of the current channel and the self-bias voltage.

CHARACTERISTICS OF THE FABRICATED SOCFED

Fig. 6 shows the forward I-V characteristics of the SOCFED with the optimized treatment condition. Also shown are the characteristics of a SBD fabricated for comparison, shown in Fig. 7. In the SBD, the epitaxial layer structure was the same as the SOCFED's. Furthermore, the anode and the cathode corresponded to the Schottky electrode and the ohmic electrode 2 in the SOCFED, respectively. However, the fluoride-based plasma treatment was not applied in the SBD. The turn-on voltage in the SOCFED was reduced to 0 V in contrast to that in the SBD of about 0.85 V.

Fig. 8 shows the reverse I-V characteristic of the SOCFED with the optimized treatment condition. As shown in Fig. 8, the current leakage at the reverse voltages was decreased lower than 1 x 10^{-3} A/mm. In addition, catastrophic breakdown did not arise at a voltage of less than -200 V, suggesting that the breakdown voltage of this SOCFED is over 200 V.

The leakage current here is not low enough for power electronics device applications. One of the suspected causes of the leakage current is damage to the AlGaN barrier layer by the fluoride-based plasma treatment. For confirmation, we evaluated the reverse I-V characteristics of the SBD. However, no significant difference in the leakage current was observed between the SOCFED and the SBD. This indicates that the leakage current is not caused by the influence of the fluoride-based plasma treatment. We thus assume that the leakage current is caused dominantly by the quality of epitaxial layers of the wafer used in this time.

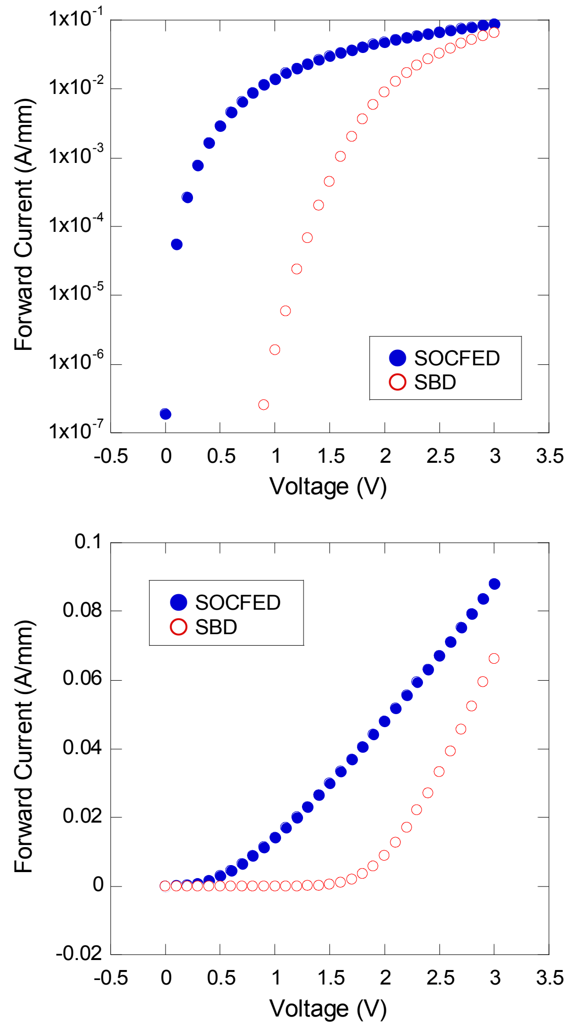

Fig. 6 Forward I-V characteristics of the SOCFED with optimized treatment condition and the SBD.

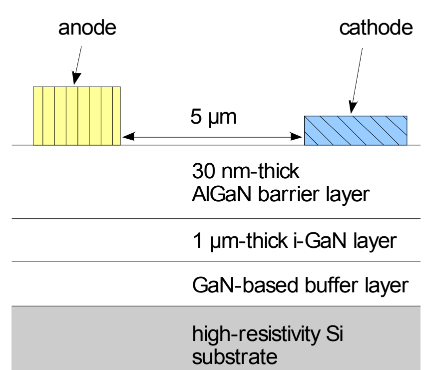

Fig. 7 Schematic cross-section drawing of the SBD.

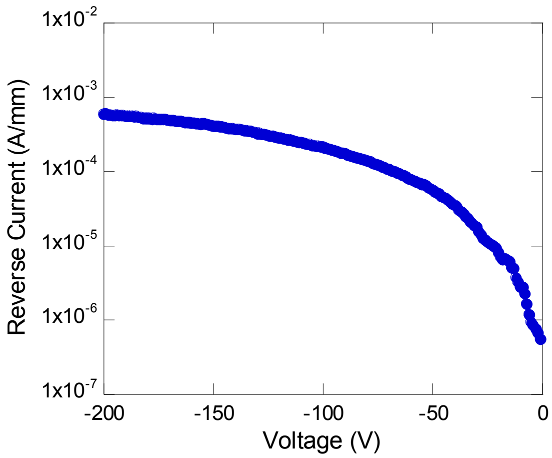

Fig. 8 Reverse I-V characteristics of the SOCFED with the optimized treatment condition.

Conclusions

We have demonstrated the novel AlGaN/GaN field-effect diode, that is, SOCFED. It has a distinguishing anode structure consisted of the Schottky-ohmic combined electrode and the relatively thick AlGaN barrier layer of 30 nm. By optimizing the condition of the fluoride-based plasma treatment to the surface of the AlGaN barrier layer underneath the Schottky electrode, a turn-on voltage of 0 V and a leakage current of less than 1 x 10^{-3} A/mm were obtained in the SOCFED. In addition, its breakdown voltage was estimated at over 200 V.

References

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Acronyms

FESBD: Field-Effect Schottky Barrier Diode
SOCFED: Schottky-Ohmic Combined anode Field-Effect Diode
FET: Field-Effect Transistor
2DEG: Two Dimensional Electron Gas
CVD: Chemical Vapor Deposition
RIE: Reactive Ion Etching
SBD: Schottky Barrier Diode