AlGaN/GaN HEMTs With Thin InGaN Cap Layer for Normally Off Operation

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***Abstract*—AlGaN/GaN HEMTs with a thin InGaN cap layer have been proposed to implement the normally off HEMTs. The key idea is to employ the polarization-induced field in the InGaN cap layer, by which the conduction band is raised, which leads to the normally off operation. The fabricated HEMT with an $In_{0.2}Ga_{0.8}N$ cap layer with a thickness of 5 nm showed normally off operation with a threshold voltage of 0.4 V and a maximum transconductance of 85 mS/mm for the device with a 1.9-μm-long gate. By etching off the $In_{0.2}Ga_{0.8}N$ cap layer at the access region using gate electrode as an etching mask, the maximum transconductance has increased from 85 to 130 mS/mm due to a reduction of the parasitic source resistance.**

***Index Terms*—AlGaN/GaN, HEMT, InGaN cap, normally off, polarization-induced field.**

I. Introduction

AlGaN/GaN HEMTs receive considerable attention for high-power and high-frequency applications because of the advantages of high breakdown voltage and high electron velocity. In order to apply them to the high-power switching system, normally off HEMTs are indispensable to realize fail-safe system to avoid the problem of circuit burn out when the gate signal becomes ground voltage [1]. The conventional normally off HEMTs require precise etching control for recess gate [2] or heavy p^+ doping for the junction gate [3]. In addition to these process requirements, the normally off HEMTs sometimes show a problem of transconductance (g_m) decrease due to a large parasitic resistance. Recently, the normally off HEMTs fabricated by fluoride-based plasma treatment have been reported [4]–[6]. This approach seems promising. However, understandings of the mechanism are not sufficient. In addition to that, it is not clear at present whether the fluorine atoms incorporated in the AlGaN barrier layer are stable or not, although the threshold voltage of the device is stable for 80 days at 200 °C [7]. Further study is required for these devices to be applied to real systems. Another approach to implement the normally off HEMTs is to take advantage of the polarization of the III–nitride material system. It has been reported that the polarization-induced electric field in the InGaN back-barrier layer could increase the confinement of the 2-D electron gas (2DEG) [8].

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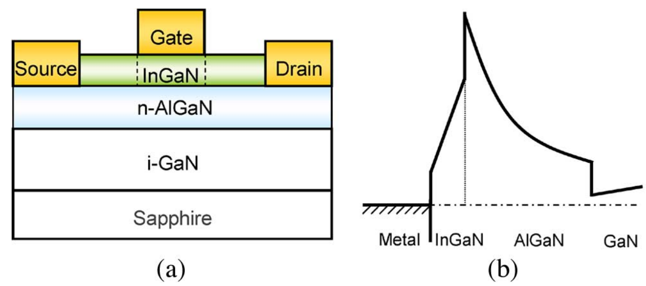

Fig. 1. (a) Schematic cross section of AlGaN/GaN HEMTs with InGaN cap layer and (b) corresponding energy band diagram.

In this letter, we propose to introduce a thin InGaN cap layer on a conventional AlGaN/GaN HEMT structure to implement the normally off HEMTs. The polarization-induced field in the InGaN cap layer is expected to raise the conduction band of the AlGaN/GaN interface, which leads to the threshold voltage shift to the positive direction. It will be possible to decrease the parasitic source resistance by removing the InGaN cap layer at the access region.

II. Experiment and Results

A schematic cross section of the proposed HEMTs and the corresponding energy band diagram are shown in Fig. 1(a) and (b), respectively. A thin layer of InGaN is grown on an n-$Al_{0.25}Ga_{0.75}N$/i-GaN heterostructure. The direction of the polarization-induced field formed in the InGaN is opposite to that in the AlGaN. Then, the conduction band is raised by the polarization-induced field in the InGaN cap layer, as shown in Fig. 1(b), which leads to normally off operation. In the case of HEMTs without the InGaN cap layer, 2DEG is formed in the AlGaN/GaN interface, which leads to the normally on operation. Then, if the InGaN cap layer is introduced only in the gate region, it is possible to decrease the source parasitic resistance even in the normally off HEMTs because the carrier in the access region is not depleted. The gate recess etching that affects the threshold voltage is not required in the present device.

The devices were fabricated on an i-$In_{0.2}Ga_{0.8}N$(5 nm)/i-$Al_{0.25}Ga_{0.75}N$ (5 nm)/n-$Al_{0.25}Ga_{0.75}N$ (2×10^{18} cm^{-3}, 10 nm)/i-$Al_{0.25}Ga_{0.75}N$ (5 nm)/i-GaN(3 μm) heterostructure grown by metal–organic chemical vapor deposition on a sapphire substrate. The $In_{0.2}Ga_{0.8}N$ thickness of 5 nm was chosen to realize a large threshold voltage shift within the limit of critical layer thickness. A control device without the $In_{0.2}Ga_{0.8}N$ cap layer was also fabricated for comparison. The AlGaN/GaN-layered structure of the control device was the same as that with

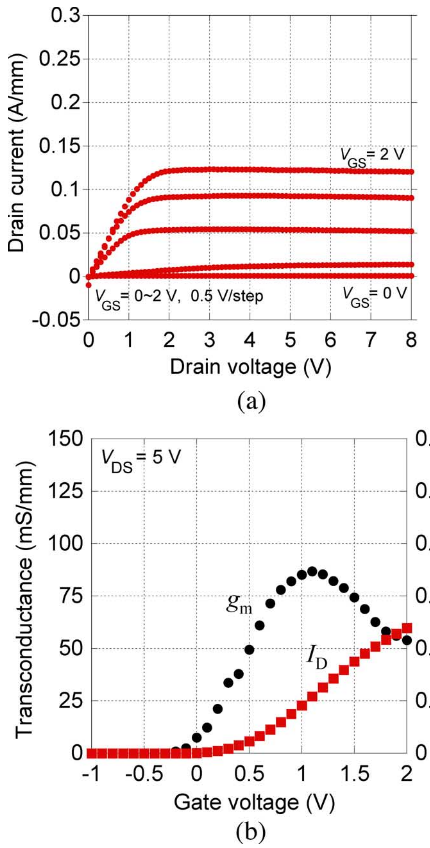

Fig. 2. (a) I_D–V_{DS} and (b) transfer characteristics of AlGaN/GaN HEMT with $In_{0.2}Ga_{0.8}N$ cap layer. The gate voltage step is (a) 0.5 V and (b) $V_{\mathrm{DS}} = 5$ V.

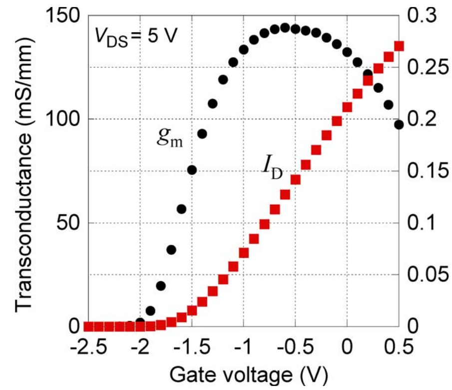

Fig. 3. Transfer characteristics of AlGaN/GaN HEMT without $In_{0.2}Ga_{0.8}N$ cap layer. $V_{\mathrm{DS}} = 5$ V.

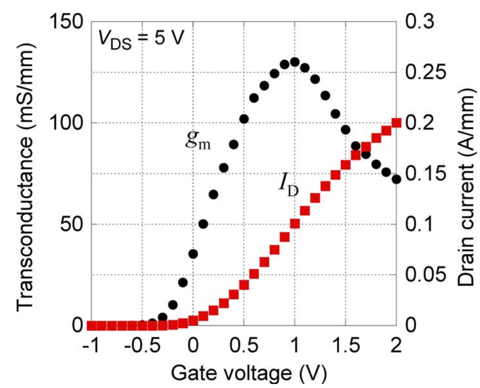

Fig. 4. Transfer characteristics of AlGaN/GaN HEMT with $In_{0.2}Ga_{0.8}N$ cap layer after etching the $In_{0.2}Ga_{0.8}N$ cap layer at the access region. $V_{\mathrm{DS}} = 5$ V.

the $In_{0.2}Ga_{0.8}N$ cap layer. The sheet resistances were 33 kΩ and 513 Ω for the wafers with and without the $In_{0.2}Ga_{0.8}N$ cap layer, respectively. The larger sheet resistance of the wafer with the $In_{0.2}Ga_{0.8}N$ cap layer is thought to be due to a reduction of the 2DEG density caused by the polarization-induced field in the $In_{0.2}Ga_{0.8}N$ cap layer. Ohmic contacts were formed by alloying Ti/Al/Ni/Au (20/120/30/50 nm) at 830 °C for 30 s in N_2 ambient. The gate electrodes were formed using Ni/Pt/Au (3/30/300 nm). The gate length was 1.9 μm. The gate–source and gate–drain distances were 1.5 and 2.4 μm, respectively.

Fig. 2(a) shows I_D–V_{DS} characteristics and Fig. 2(b) shows I_D–V_{GS} and g_m–V_{GS} transfer characteristics of HEMTs with the $In_{0.2}Ga_{0.8}N$ cap layer. Normally off operation with a threshold voltage of 0.4 V, which was evaluated by extrapolating I_D–V_{GS} curve to zero I_D, was confirmed, as shown in Fig. 2(b). The maximum transconductance $(g_{m\,\max})$ was 85 mS/mm. The gate leakage current was comparable with that of the control device without the InGaN cap layer. Fig. 3 shows the results of the device without the $In_{0.2}Ga_{0.8}N$ cap layer. In this case, normally on operation with a threshold voltage of -1.5 V and $g_{m\,\max}$ of 145 mS/mm was obtained. This means that the $In_{0.2}Ga_{0.8}N$ cap layer caused a threshold voltage shift of about 1.9 V, which was comparable with that of 1.6 V calculated by considering the polarization-induced field. The smaller g_m of the device with the $In_{0.2}Ga_{0.8}N$ cap layer than that of the device without the $In_{0.2}Ga_{0.8}N$ cap layer is probably due to a large parasitic source resistance that results from the reduced 2DEG density caused by the $In_{0.2}Ga_{0.8}N$ cap layer in the access region.

The $In_{0.2}Ga_{0.8}N$ cap layer was removed by Cl_2 reactive ion etching using the gate electrode as an etching mask to decrease the parasitic source resistance. The measured transfer characteristics after etching the $In_{0.2}Ga_{0.8}N$ cap layer at the access region are shown in Fig. 4. The maximum transconductance increased from 85 to 130 mS/mm. These results indicate the validity of the HEMTs with InGaN cap layer for realizing normally off HEMTs with small parasitic source resistance. A threshold voltage shift of -0.3 V toward the negative direction was observed after etching the $In_{0.2}Ga_{0.8}N$ cap layer at the access region. Although the origin of the threshold voltage shift is not clear at present, it may have some relation with the local strain relaxation by etching the $In_{0.2}Ga_{0.8}N$ cap layer at the access region. More detailed studies are necessary for determining the actual mechanism of threshold voltage shift to the negative direction.

III. Summary

AlGaN/GaN HEMTs with a thin InGaN cap layer have been proposed to implement the normally off HEMTs. The polarization-induced field in the InGaN cap layer was employed to raise the conduction band, which results in a normally off operation. The fabricated HEMT with an $In_{0.2}Ga_{0.8}N$ cap layer with a thickness of 5 nm showed normally off operation with a threshold voltage of 0.4 V and a maximum transconductance of 85 mS/mm for the device with a 1.9-μm-long gate. By etching off the $In_{0.2}Ga_{0.8}N$ cap layer at the access region using the gate electrode as an etching mask, the maximum transconductance has increased from 85 to 130 mS/mm due to a reduction of the parasitic source resistance. These results indicate the validity of introducing an $In_{0.2}Ga_{0.8}N$ cap layer to implement the normally off HEMTs.

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