Effects of Electronic States at Insulator/AlGaN Interfaces on Threshold Voltage Instability of Al₂O₃/AlGaN/GaN Structures

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Abstract

This paper presents the effects of the inductively coupled plasma (ICP) etching of AlGaN surface on the resulting threshold voltage (V_{TH}) instability of Al₂O₃/AlGaN/GaN structures. It was found from the measured capacitance – voltage (C–V) characteristics that the ICP etching of the AlGaN surface showed larger V_{TH} shifts than in the sample without ICP etching. Using a calculation method for describing C–V characteristics, we also analyzed this V_{TH} shifts. It is likely that the deep negatively charged acceptor-like states originating from interface states at Al₂O₃/AlGaN caused V_{TH} shifts toward the positive bias direction.

1. Introduction

For the past few years, AlGaN/GaN high electron mobility transistors (HEMTs) have been extensively studied, leading to major technological advances in terms of high-power, high-efficiency, and high-linearity operation. In spite of these significant developments, however, there are several remaining stability issues, such as threshold voltage (V_{TH}) instability and current collapse, impeding the widespread deployment of these GaN-based devices. There have been few reports on metal-insulator-semiconductor (MIS) interface properties of the AlGaN/GaN MIS HEMTs and their relationship to the resulting V_{TH} instabilities has not been discussed in detail. In this work, we have investigated the effects of the Cl₂-based inductively coupled plasma (ICP) etching of AlGaN surface on the resulting V_{TH} instability of Al₂O₃/AlGaN/GaN structures.

2. Experiment

An undoped Al₀.₂Ga₀.₈N/undoped GaN heterostructure with an AlGaN layer thickness of 34 nm grown on a sapphire substrate illustrated in Fig. 1 was used in this work. The AlGaN surface was etched by inductively coupled plasma (ICP) etching process using a Cl₂/BCl₃ gas mixture. The etching depth was 7 nm. A 20 nm-Al₂O₃ film was deposited on the AlGaN surface using atomic layer deposition system. The C–V calculation was carried out taking into account the fixed charges at the AlGaN/GaN interface originating from spontaneous and as well as the charge in the electronic states at the Al₂O₃/AlGaN interface [1-3].

2. Results & discussion

To characterize the Al₂O₃/AlGaN/GaN structures, we initially performed a conventional C–V measurement at room temperature (RT) at a measurement frequency of 10 kHz (not shown here) [4]. Both samples showed C–V curves with two steps, peculiar to the MIS structure fabricated on the heterostructure including a two–dimensional electron gas [2,3]. For the ICP-etched sample we observed a less steep slope of the C–V curve and a high on-set voltage at the forward bias regime [4]. The relatively slower increase in capacitance with increasing forward bias voltage suggests the presence of higher state densities at the Al₂O₃/ICP-etched AlGaN interface. Using the numerical fitting of C–V curves, we have attempted to obtain the interface state densities D_S(E) of the Al₂O₃/AlGaN interfaces. The measured C–V curves could be well fitted with the fitting curves (not shown here). The state density distribution at the Al₂O₃/AlGaN interface showed that the ICP etching of the AlGaN surface significantly increased the interface state density (not shown here). The detailed discussion about the experimentally measured C–V curves and the fitting result has been published elsewhere [4].

To investigate the effects of the electronic states at Al₂O₃/AlGaN interface on the resulting V_{TH} instability in Al₂O₃/AlGaN/GaN structures, the C–V measurement was performed with the bias swing from various maximum voltages (V_{MAX}) to the negative bias direction. Figure 2 (a) and (b) shows the dependence of V_{TH} on V_{MAX} of the experimentally measured C–V characteristic with and without etching of the AlGaN surface. Both sample showed parallel C–V shifts (V_{TH} shift) toward the positive bias direction with increasing V_{MAX}. In the ICP-etched sample shown in Fig. 2, we observed a larger V_{TH} shift than in the sample without ICP etching.
duced a larger assumed electronic states at the Al2O3/AlGaN interfaces obtained from numerical fitting of C–V characteristics [4]. The calculated C–V curves of the dependence of \( V_{\text{TH}} \) on \( V_{\text{MAX}} \) are shown in Fig. 3. Both calculated C–V curves showed parallel \( V_{\text{TH}} \) shift toward the positive bias direction with increasing \( V_{\text{MAX}} \). In the ICP etched sample shown in Fig. 3, we reproduced a larger \( V_{\text{TH}} \) shift than in the sample without ICP etching. The calculated results are in qualitative agreement with the experimentally measured C–V curves shown in Fig. 2.

Figure 4 illustrates the charge condition of the interface states at Al2O3/AlGaN and potential distribution at gate bias, (a) \( V_G = 0 \) V and (b) \( V_G = 2 \) V at RT, to understand in the dependence of \( V_{\text{TH}} \) on \( V_{\text{MAX}} \) of the C–V characteristics shown in Figs. 2 and 3. Electrons in energies above Fermi level \( (E_F) \), which is acceptor-like traps, can change their charge state \( (N_A^0/N_A) \) accordingly with the gate voltage sweep. The acceptor-like states in this energy region produce excess negative charge state when electrons are trapped, whereas they are in the neutral charges state when electrons are detrapped, mainly causing a stretch out and a high on-set voltage of the C–V curve at the forward bias. On the other hand, the electrons in energies below \( E_F \) of acceptor-like traps remain trapped act as negatively fixed charges \( (N_A^0) \). The higher the \( V_G \), the closer the Fermi level is to the conduction band edge of AlGaN, and the more acceptor-like states are filled \( (N_A^0) \).

To confirm this peculiar C–V shifts behavior, we carried out numerical C–V calculations, taking into account the bias swing from various \( V_{\text{MAX}} \) to the negative bias direction. We assumed electronic states at the Al2O3/AlGaN interfaces obtained from numerical fitting of C–V characteristics [4]. The calculated C–V curves of the dependence of \( V_{\text{TH}} \) on \( V_{\text{MAX}} \) are shown in Fig. 3. Both calculated C–V curves showed parallel \( V_{\text{TH}} \) shift toward the positive bias direction with increasing \( V_{\text{MAX}} \). In the ICP etched sample shown in Fig. 3, we reproduced a larger \( V_{\text{TH}} \) shift than in the sample without ICP etching. The calculated results are in qualitative agreement with the experimentally measured C–V curves shown in Fig. 2.

3. Conclusions

In summary, we have investigated the effects of the ICP etching of AlGaN surface on the resulting \( V_{\text{TH}} \) instability in Al2O3/AlGaN/GaN structures. It was found from the experimentally measured C–V characteristics results that the ICP etching of the AlGaN surface showed larger \( V_{\text{TH}} \) shifts than in the sample without ICP etching. Using a calculation method for describing C–V characteristics, we also analyzed this \( V_{\text{TH}} \) shifts. It is likely that the deeper negatively charged acceptor-like states originating from interface states at Al2O3/AlGaN caused \( V_{\text{TH}} \) shifts toward the positive bias direction. On the basis of a systematic characterization of interface states, further investigation is absolutely necessary to control electronic states at insulator/AlGaN interfaces for improved \( V_{\text{TH}} \) instability of AlGaN/GaN MIS HEMTs.

References