Improved Gate leakage and Microwave Performance by Inserting A Thin Erbium oxide layer on AlGaN/GaN/Silicon HEMT Structure

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ABSTRACT

We report on AlGaN/GaN/Silicon heterostucture Metal-Oxide-Semiconductor high electron mobility transistor (MOS-HEMT) using electron-beam (e-beam) deposited high dielectric constant (High-K) erbium oxide layer as the gate, the Er\textsubscript{2}O\textsubscript{3} inserted layer dielectric constant developed in this study was 10.1. Moreover, exhibit improved device characteristics performance, as compared with the conventional high electron mobility transistor (HEMT).

INTRODUCTION

Gallium nitride (GaN)–based wide-gap semiconductor devices are becoming common building blocks in optoelectronics and microelectronic engineering, especially for the fabrication of high electron mobility transistors (HEMTs)\textsuperscript{1,2}. For microwave power applications, AlGaN/GaN HEMT devices must exhibit high linearity, a high breakdown field. Because the gate leakage current is the factor that limits the power performance of HEMT devices\textsuperscript{3}, several approaches have been proposed to decrease gate leakage through the incorporation of a variety of gate oxide/insulators, including electron beam (EB)–evaporated Gd\textsubscript{2}O\textsubscript{3} \textsuperscript{4} plasma-enhanced chemical vapor–deposited Si\textsubscript{3}N\textsubscript{4} and SiO\textsubscript{2} \textsuperscript{5}, atomic layer–deposited HfO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} \textsuperscript{6}.

Notably, a comparatively good EB-evaporated oxide featuring a low interface state density on GaN has been realized \textsuperscript{1}. Erbium oxide (Er\textsubscript{2}O\textsubscript{3}), which has a high dielectric constant of 10–12.4 and is highly insulating with a band gap energy of 7.8 eV \textsuperscript{8}. Hwang et al. have described the basic properties of Er\textsubscript{2}O\textsubscript{3} dielectrics on InGaAs channels for capacitor applications \textsuperscript{9}. In this paper, we describe the EB-evaporation of Er\textsubscript{2}O\textsubscript{3} in situ with Ni/Au metals onto AlGaN/GaN heterostructures and their resulting DC and RF characteristics, which we compare with those of conventional devices.

DEVICE STRUCTURE AND FABRICATION

The structure of the Er\textsubscript{2}O\textsubscript{3}/AlGaN/GaN MOS-HEMT is displayed in Fig. 1. The epitaxial structure was grown through metal-organic chemical vapor deposition (MOCVD) on a highly resistive (> 6000 \(\Omega\)) 6-inch P-type silicon (111) substrate. A standard low-temperature AlN nucleation layer, a 1-µm GaN buffer layer, together with a channel layer, and a 48-nm AlGaN barrier layer were grown sequentially. All (Al)GaN layers were unintentionally doped.

![Figure 1: The Schematic cross of the Er\textsubscript{2}O\textsubscript{3} MOS-HEMT structure.](image-url)

The designed structure exhibited a sheet charge density of 1.696 \times 10^{13} \text{cm}^{-2} and a hall electron mobility of 1280 \text{cm}^{2} \text{V}^{-1} \text{s}^{-1} at 300 K. Atomic force microscopy (AFM) was used to reveal the surface morphology of the Er\textsubscript{2}O\textsubscript{3}/AlGaN/GaN on-Si heterostructure which is shown in Fig. 2. Excellent root-mean-square (rms) roughness of...
1.375nm and 1.909nm are observed in a 1×1 um² and 5×5 um² area, respectively. The Er₂O₃ thin film was obtained from EB-evaporated erbium under an oxygen flow rate of 10 sccm in a high vacuum chamber (2 × 10⁻⁶ Torr).

The device isolation was accomplished through mesa dry etching down to the unintentionally doped-GaN layer in a BCl₃ plasma reactive ion etching chamber. Ohmic contacts of Ti/Al/Ni/Au (19/120/30/75 nm) metals were deposited through EB evaporation, followed by rapid thermal annealing at 850 °C for 30s in a nitrogen-rich chamber. After gate lithography pattern formation and surface cleaning, the samples were immediately loaded into the EB deposition chamber and then 20-nm-thick erbium was first evaporated at an optimized oxygen flow rate of 10 sccm. Then the chamber pressure increased to approximately 10⁻³ torr. Next, the chamber pressure was decreased to 2 × 10⁻⁶ Torr and the Ni/Au (70/140 nm) gate metals were deposited. For comparison, a conventional Ni/Au Schottky gate AlGaN/GaN-HEMT was also fabricated. Finally, the Ti/Au (50/1100 nm) metal were deposited for interconnection and probe pads. Device characteristics were measured at room temperature in the dark using an Agilent B1500A semiconductor device analyzer (for DC characteristics) and an Agilent N1301A C-V analyzer (for C-V characteristics).

The X-ray photoelectron spectroscopy (XPS) was used to study the interfacial reaction and out-diffusion of the thin (20 nm) Er₂O₃ layer on AlGaN. Figure 3 presents the 4d core level of the Er₂O₃ thin film; the binding energy was 167.3 eV [10]. Devices were processed using conventional optical lithography and a lift-off technology.

Figure 2: AFM top view in (a) 1x1 μm² and (b) 5×5 um² area showing the surface morphology of Er₂O₃/AlGaN/GaN grown on silicon.

Figure 3: The 4d core levels XPS spectra of Er₂O₃.

Figure 4: Measured C-V characteristic of the Er₂O₃ – MOSHEMT.
Figure 4 shows the capacitance–voltage (C–V) characteristic of an MOS capacitor having a diameter of 100 μm at 1MHz frequency. The sharp transition from accumulation to depletion reveals a few pinning phenomena of the Fermi level at the Er₂O₃–AlGaN interface and suggests a high quality interface.² We employed the series total capacitance

$$\frac{1}{C_{\text{total}}} = \frac{1}{C_{\text{ox}}} + \frac{1}{C_{\text{AlGaN}}}$$

(1)
to obtain the capacitance of the Er₂O₃ oxide layer, using the measured value of the accumulation capacitance at the zero bias of the AlGaN layer and the Er₂O₃ layer capacitance. The capacitance of the AlGaN Schottky layer (AlGaN dielectric constant: 9) was approximately 26 pF; we estimated the value of $C_{\text{total}}$ to be 15 pF. Thus, according to equation (1), the capacitance of Er₂O₃ ($C_{\text{ox}}$) was 35.4 pF. Therefore, the dielectric constant of 20-nm-thick Er₂O₃ was 10.1.³ We tested 1.0-μm-long gate-length devices with both conventional HEMT and Er₂O₃ MOS-HEMT structures on-wafer and characterized them through DC measurements. Figure 5 represents the gate current–voltage characteristics of the Er₂O₃ MOS-HEMT and the conventional HEMT. The value of $V_{\text{on}}$ of the Er₂O₃ MOS-HEMT, defined by a gate current of 1 mA/mm, was 4.38 V; for the conventional HEMT, this value was only 1.56 V. Furthermore, the reversed gate-to-drain breakdown voltages ($V_{\text{br}}$), defined by gate leakage current reaching 1 mA/mm, for the conventional HEMT and the Er₂O₃ MOS-HEMT were −86 V and −127 V, respectively. The inset in Fig. 5 shows the gate leakage current density of Er₂O₃ MOS-HEMT as low as $2.97 \times 10^{-8}$ mA/mm at -10V gate bias, which is four order of magnitude smaller than that of conventional-HEMT.

To investigate the gate control characteristics of the HEMTs. The subthreshold swing (SS) is a parameter that indicates how effectively a device can be turned off. Herein, we define the SS as the decrease in the log ($I_{\text{d}}$)–$V_{\text{g}}$ plot near the cut-off voltage of the device which is shown in Fig. 8.

Figure 7 displays the typical transistor $I_{\text{d}}$–$V_{\text{ds}}$ characteristics of the two devices. Under the conditions of a drain bias ($V_{\text{ds}}$) from 0 to 20 V and a gate bias ($V_{\text{gs}}$) from −6 to +2 V, the maximum drain-to-source current densities ($I_{\text{d,max}}$) of the conventional HEMT and the Er₂O₃ MOS-HEMT were 590 and 628 mA/mm, respectively. The conventional HEMT and the Er₂O₃ MOS-HEMT were completely pinched-off at voltages of −4.5 and −6.5 V, respectively.

![Figure 7: Ids-Vds characteristics of both devices.](image)

![Figure 8: The drain-current on the gate-source voltage of the](image)
We measured the drain current ($I_{ds}$) as a function of the gate-to-source voltage ($V_{gs}$) for both devices biased at a value of $V_{ds}$ of 10V. The $I_{ON}/I_{OFF}$ ratio and subthreshold swing of the Er$_2$O$_3$ MOS-HEMT (1.2 x 10$^7$ and 125 mV/dec, respectively) were superior to those of the conventional HEMT (5 x 10$^3$ and 353 mV/dec, respectively). Figure 8 also reveals that the leakage current decreased by more than three orders of magnitude after insertion of the Er$_2$O$_3$ thin film. We extracted the subthreshold swing (SS) of the HEMT device from its transfer characteristics in the subthreshold regime, using the equation (2).

$$SS = \frac{\partial V_{gs}}{\partial \log I_d}$$ (2)

We also measured the on-wafer microwave S-parameters of the 1.0-μm-long gate devices in a common source configuration using an HP 8364 network analyzer in conjunction with Cascade direct probes shown in Fig.9.

![Figure 9: The microwave s-parameters of the Er$_2$O$_3$ MOS-HEMT and HEMT.](image)

Figure 9: The microwave s-parameters of the Er$_2$O$_3$ MOS-HEMT and HEMT.

We obtained a maximum current gain cut-off frequency ($f_1$) of 17 GHz and a maximum oscillation frequency ($f_{max}$) of 24 GHz for the Er$_2$O$_3$ MOS-HEMT under the maximum $g_m$ bias point at values of $V_{ds}$ and $V_{gs}$ of 10 and −3.8 V, respectively. In contrast, the values of $f_1$ and $f_{max}$ of the conventional HEMT were 7.6 and 17 GHz, respectively, under the maximum $g_m$ bias point at values of $V_{ds}$ and $V_{gs}$ of 10 and −2.6 V, respectively.

CONCLUSIONS

In this study, we prepared high-$k$ Er$_2$O$_3$ layers through EB evaporation under a high oxygen flow rate and applied them in AlGaN/GaN HEMTs on silicon substrate. The Er$_2$O$_3$ dielectric layer was confirmed through the XPS Er 4d core level spectra. The fabricated Er$_2$O$_3$ MOS-HEMT exhibited superior DC and RF performances relative to those of a conventional HEMT. Moreover, the gate leakage was more than four orders of magnitude lower than that of the conventional HEMT under similar bias conditions, suppressed by the wide band gap of the Er$_2$O$_3$ dielectric.

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REFERENCES


ACRONYMS

HEMT: High Electron Mobility Transistor
SS : Subthreshold Swing