All Epitaxy Nd2O3 /AlGaN/GaN MOSHEMT: Increased Linearity and Thermal Stability

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Abstract

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Abstract—This letter reports electrical properties of AlGaN/GaN high electron mobility transistor (HEMT) with epitaxial Nd$_2$O$_3$ as a gate insulator. The introduction of Nd$_2$O$_3$ between metal and semiconductor in the gate region, results in two orders of magnitude reduction of gate leakage current, which remains unchanged even at higher temperature of 200°C. The I$_{ON}$/I$_{OFF}$ also remains constant at 200°C and the transconductance stays at its peak over a significant range of gate bias (4.5 V). This linearity is attributed to the increased electron concentration in channel due to introduction of epitaxial Nd$_2$O$_3$ and the resulting strain on AlGaN barrier layer. The increased 2DEG density also leads to an increase in output drain current from the metal oxide semiconductor (MOS)-HEMT.

Index Terms—MOSHEMT, Strain engineering, Nd$_2$O$_3$, thermal stability, HEMT linearity

I. INTRODUCTION

Because of its high saturation velocity, high thermal conductivity and large breakdown field, AlGaN/GaN high electron mobility transistor (HEMT) finds application in high power devices that can operate at high frequencies and high temperatures. [1] One of the ways to achieve gate control in HEMT is to use a metal semiconductor (MS) schottky contact. However one of the biggest challenges in improving the performance of MS-HEMT has been large gate leakage current, which eventually leads to low frequency noise [2] and low breakdown voltage of device.

One of the possible solutions to reduce leakage current in HEMT is to use an amorphous oxide as a gate dielectric. However, the use of amorphous oxides comes with its own set of challenges such as non-linearity in transfer characteristics, thermal stability [15], [16]. The nonlinearity in MOSHEMTs can pose severe reliability issues during its operation. For example, in case of in communication systems, nonlinearity in transfer characteristics complicates the design process at the circuit level [6]. Linearity in HEMT transfer characteristics has been accomplished in the past by using a double 2DEG layers within the HEMT heterostructure [4], and in FinFET [5]. However, these approaches increase the complexity in the hetrostructure growth of HEMT and also the fabrication becomes very challenging especially, the FinFET.

Due to the low thermal stability of amorphous oxides, there is an increase in gate leakage current at an elevated temperature of operation of MOSHEMT [15], [16] leading to a decrease in $I_{ON}/I_{OFF}$ ratio. Further, these amorphous oxides tend to crystallize at high temperature ohmic-contact annealing and this crystallization again leads to an increase in gate leakage current.

Nd$_2$O$_3$ is a rare earth (Lanthanide) oxide that can be grown epitaxially using a solid source molecular beam epitaxy (MBE). It also exhibits good interface on silicon in literature [8], [10]. An epitaxial Gd$_2$O$_3$, high-k dielectric growth on AlGaN/GaN heterostructure, has shown to have good thermal stability for MOSHEMT [3].

In this letter, we report Nd$_2$O$_3$ as a gate oxide for AlGaN/GaN MOSHEMT. The DC performance of the Epitaxial Nd$_2$O$_3$/AlGaN/GaN MOSHEMT is compared with a conventional Ni/Au based MSHEMT as the control sample both at room temperature and at an elevated temperature of 200°C.

II. GROWTH AND DEVICE FABRICATION

Figure 1(a) shows the schematic diagram of the AlGaN/GaN heterostructure on 4H-SiC substrate grown by RIBER C21 PA-MBE system. The grown heterostructure is capped with 2 nm GaN layer to stave off the oxide formation at the top surface of AlGaN layer. After AlGaN/GaN HEMT structure growth, Nd$_2$O$_3$ thin films were grown in a cluster MBE system (DCA, Finland). We carried out an in-situ preparation of AlGaN/GaN virtual substrate at 750°C which is followed by the growth of epitaxial Nd$_2$O$_3$ at 650°C by e-beam heating with an additional oxide partial pressure of 5×10$^{-7}$ mbar. The thickness of the oxide was taken to be 5.2 nm. Figure 2(a) shows the out-of-plane XRD plot of the entire MOSHEMT heterostructure. The separation between the drain and source is 15 micron and the gate length is 4 micron. Ohmic contact comprising Ti/Al/Ni/Au (25/120/40/50 nm) metal stacks for source and drain was deposited after first level optical lithography. Subsequently, the metal stack was annealed at 830°C for 30 sec in nitrogen ambient. Finally, the gate of Ni/Au (30/300 nm) was deposited using electron beam evaporation after second-level optical lithography.
III. RESULTS AND DISCUSSION

The band gap and conduction band offset of Nd2O3 with respect to GaN as estimated by XPS analysis were found to be 4.57 and 2.4 eV respectively. Figure 1(b) represents the schematic of band-alignment between epi-Nd2O3 and GaN. The in-plane XRD, as shown in figure 1(d) confirms the hexagonal nature of epi-Nd2O3.

All the electrical measurements were carried out using Agilent B1500A semiconductor device parameter analyzer. Figure 3(b) shows the transfer characteristics (\(I_D V_{GS}\) at \(V_{DS}=7\) V) for MOSHEMT and Ni/Au MSHEMT. A reduction of around two orders of magnitude is observed in \(I_{off}\) of MOSHEMT as compared to that of control sample. The lower \(I_{off}\) of MOSHEMT as compared to control sample is attributed to the reduction in gate leakage current (\(I_G\)) as compared to control sample (figure 3(a)). The conduction band offset of 2.4 eV of Nd2O3 is one of the reasons for reduction in reverse biased gate leakage as compared to control sample.

As MOSHEMT is meant to be used as a high power device, channel temperature may rise above 100°C during the operation of the device [14]. To check the thermal stability of MOSHEMT, transfer and output characteristics measurements were performed at elevated temperatures (200°C) as shown in figure 3. As can be seen in figure 3, there is no increase in the gate leakage current \(I_G\) and subsequently \(I_{off}\), at an elevated temperature of 200°C. The significant improvement of thermal stability of MOSHEMT is due to the single crystalline nature of Nd2O3 [3]. The \(I_{on}/I_{off}\) remains unchanged at 28°C and at 200°C [3]. This confirms the stability of Epi-Nd2O3 as compared to the MOSHEMT characteristics reported in the literature [15], [16]. The drop of \(I_{on}\) at 200°C is due to the stronger polar optical phonon scattering in the channel at elevated temperature [3], [13].

The gate voltage swing(GVS) can be taken as 80% of maximum value of transconductance. As shown in figure 4(b) by this criterion the GVS comes out to be 4.5 V. Epitaxial Nd2O3 grown on AlGaN/GaN heterostructure certainly plays the critical role in improving the MOSHEMT electrical characteristics. The introduction of epitaxial Nd2O3 on HEMT heterostructure introduces an in-plane tensile strain in the AlGaN barrier layer as the lattice constant of hexagonal phase of Nd2O3 is larger than in-plane lattice constant of wurtzite GaN. This in-plane tensile strain induces a compressive strain along c-axis which is estimated from the high resolution XRD as shown in figure 2(b). The in-plane compressive strain results an increase in piezoelectric polarization in the AlGaN barrier layer. This increased polarization leads to an increase in 2DEG density [7]. But as can be seen in CV plot in figure 5(b), the 2DEG density under the gate actually decreases for
MOSHEMT leading to an increase in the channel resistance under the gate.

To explain this, the $R_{ON}$, which is measured using gate probe method [9], can be seen to remain constant for MOSHEMT as compared to the control sample in figure 4(a). As the channel resistance underneath the gate for the control sample is lower than MOSHEMT, it is the parasitic source and drain access resistance that is increasing for the control sample but not for MOSHEMT as shown in inset of figure 4(a). Considering that access resistance is inversely proportional to 2DEG density in access regions [19], the 2DEG density in these access regions increases because of introduction of epi-Nd$_2$O$_3$. Source access resistance is measured by injecting current from the gate to the source and keeping the drain floating [17]. For the control sample, a lower channel resistance underneath the gate for the control sample as compared to MOSHEMT leads to lower value of $R_{ON}$ for $V_{GS}$ less than 1.07 V. On the other hand, in MOSHEMT, a lower value of $R_{ON}$ for $V_{GS}$ greater than 1.07 V leads to a higher drain current as shown in 5(a) at $V_{GS}$ equals 1.2 V. Also, a constant source access resistance in turn, results in the extrinsic transconductance linearity [11], [18].

Further, to calculate $D_{it}$ at the Nd$_2$O$_3$/GaN interface CV measurement was done at 100 kHz and 1 MHz to find out the dispersion in frequency $\Delta V$ [12]. The measured value of $D_{it}$ comes around $2.5 \times 10^{-13} \text{ cm}^{-2}$. The positive shift in $V_{th}$ can be attributed to negative charges stored in acceptor type states at oxide-GaN interface. To calculate the dielectric constant of Nd$_2$O$_3$ CV measurements of both MSHEMT and MOSHEMT were done at 1 MHz frequency and considering the oxide and AlGaN barrier layers are in series, the dielectric constant of the Nd$_2$O$_3$ layer was found to be 21.

IV. CONCLUSION

In this work, it was shown that Nd$_2$O$_3$ MOSHEMT has improved DC performance as compared to control sample, thermal stability and linearity. The linearity achieved was with the use of epitaxial oxide as gate insulator on planar AlGaN/GaN HEMT rather than change in the AlGaN/GaN HEMT heterostructure or through the use of FinFET thereby simplifying the overall process of fabricating the transistor. The maximum output current achievable from a conventional HEMT is limited by parasitic access resistance increase, but in case of Nd$_2$O$_3$ MOSHEMT this increase in access resistance was not there atleast upto certain $I_D$ value. Thus, Nd$_2$O$_3$ MOSHEMT offers many advantages which makes it an attractive candidate for high power, high frequency applications.

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