High Quality SiO$_2$/Al$_2$O$_3$ Gate Stack for GaN MOSFET

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1. Introduction

GaN MOSFET with normally-off operation is an excellent candidate for high power devices. To realize high performance GaN MOSFET, a high quality gate insulator is required. We have shown a high integrity SiO$_2$ gate insulator on GaN, which has a low interface state density ($D_i$) of SiO$_2$/GaN, a high breakdown electric field, and a high charge-to-breakdown ($Q_{bd}$), respectively, formed by Microwave (2.45 GHz: MW) Plasma Enhanced Chemical Vapor Deposition (PECVD) so far [1]. Furthermore, we have also demonstrated an AlGa$_x$/Ga$_{1-x}$N/GaN hybrid MOS-HFET [2-4] with a high field-effect mobility of 161 cm$^2$/Vs by applying the SiO$_2$ gate insulator deposited by MW-PECVD. However, the $D_i$ of SiO$_2$/GaN is higher compared with Si devices and it should be reduced. Recently, GaN MOSFET with Al$_2$O$_3$ gate insulator has been demonstrated [5, 6]. Al$_2$O$_3$ is one of the good candidates as a gate insulator of GaN MOSFET for high field-effect mobility [7]. In this paper, we report on the experimental demonstration of applying Al$_2$O$_3$ to GaN MOSFET.

2. Experiments

In order to investigate the interface properties of gate insulator/GaN and the electrical characteristics of insulators, n-type GaN on Si (111) substrates were applied for fabrication of GaN MOS capacitors. Al$_x$O$_y$ and SiO$_2$ were formed by Atomic Layer Deposition (ALD) and MW-PECVD, respectively. We also applied some gate insulators to AlGa$_x$/Ga$_{1-x}$N/GaN hybrid MOS-HFET, the structure of which is shown in Fig. 1. After mesa etching and recessed region etching to define the channel region by RIE, gate insulators were formed. Then gate, source and drain electrodes were fabricated.

3. Results and Discussions

Fig. 2 shows the energy distribution of the interface state density ($D_i$) of Al$_2$O$_3$/GaN and SiO$_2$/GaN. The thicknesses of Al$_2$O$_3$ and SiO$_2$ films were 50-60 nm. Al$_2$O$_3$ and SiO$_2$ films were annealed at 700$^\circ$C and 800$^\circ$C after deposition, respectively. $D_i$ is estimated by applying the Terman method to the Capacitance-Voltage (C-V) characteristics at 150$^\circ$C [8]. The $D_i$ of the GaN MOS capacitor with Al$_2$O$_3$ is lower than that with SiO$_2$. Fig. 3 shows the Current density-Field characteristics (J-E) of those GaN MOS capacitors at room temperature. The breakdown field of Al$_2$O$_3$ is much lower and the leakage current is much higher compared with SiO$_2$. From these results, SiO$_2$/Al$_2$O$_3$ stacked layer structure is employed for good interface property and high insulating in GaN MOSFET. In this experiment, 3 nm Al$_2$O$_3$ formed on GaN and 60 nm SiO$_2$ was deposited on Al$_2$O$_3$. After SiO$_2$/Al$_2$O$_3$ deposition, 700$^\circ$C annealing was performed. Fig. 4 shows the $D_i$ of SiO$_2$/Al$_2$O$_3$/GaN, Al$_2$O$_3$/SiO$_2$/GaN and SiO$_2$/GaN, respectively. The $D_i$ of SiO$_2$/Al$_2$O$_3$/GaN is almost the same as Al$_2$O$_3$/GaN. Fig. 7 and Fig. 8 are the J-E characteristics of these GaN MOS capacitors, respectively. The breakdown field and $Q_{bd}$ of the GaN MOS capacitor with SiO$_2$/Al$_2$O$_3$ are almost the same as SiO$_2$. These results indicate the SiO$_2$/Al$_2$O$_3$ gate stack has a low-interstate density between the structure and GaN, a high-breakdown field, and a high $Q_{bd}$.

Fig. 7 shows the transfer characteristics of AlGa$_x$/Ga$_{1-x}$N/GaN hybrid MOS-HFETs with SiO$_2$/Al$_2$O$_3$ gate stack and SiO$_2$ and Fig. 8 shows the field-effect mobility evaluated from the transfer characteristics of these MOS-HFETs. Both MOS-HFETs show good normally-off operations with the threshold voltage of about 4.2 V. The on-state characteristic of MOS-HFET with SiO$_2$/Al$_2$O$_3$ is superior to that with SiO$_2$. The field-effect mobility of MOS-HFET with SiO$_2$/Al$_2$O$_3$ is higher in all channel length and the MOS-HFET has the maximum field-effect mobility with 192 cm$^2$/Vs at the channel length of 50 $\mu$m.

4. Conclusion

We have demonstrated a high quality gate insulator for GaN MOSFET by applying SiO$_2$/Al$_2$O$_3$ gate stack. We also demonstrated an AlGa$_x$/Ga$_{1-x}$N/GaN hybrid MOS-HFET with a high field-effect mobility by applying this dielectric stack.

References

Si (111) Substrate
GaN-based Buffer
Si (111) Substrate

Fig. 1. A schematic cross section of AlGaN/GaN hybrid MOS-HFET. SiO$_2$/Al$_2$O$_3$ stack structure gate insulator was applied.

Fig. 2. $D_{it}$ of GaN MOS capacitors with SiO$_2$ and Al$_2$O$_3$, calculated from the $C-V$ characteristics at 150°C. $D_{it}$ of Al$_2$O$_3$ is lower than that of SiO$_2$.

Fig. 3. $J-E$ characteristics of GaN MOS capacitors with SiO$_2$ and Al$_2$O$_3$. Electric field is defined. $(V_g-V_{FB})/EOT$ ($V_g$: gate voltage, $V_{FB}$: flatband voltage shift, EOT: equivalent oxide thickness) The breakdown field of Al$_2$O$_3$ single layer is much lower and the leakage current is much higher than SiO$_2$.

Fig. 4. $D_{it}$ of GaN MOS capacitors with SiO$_2$, Al$_2$O$_3$ and SiO$_2$/Al$_2$O$_3$ calculated from the $C-V$ characteristics at 150°C. $D_{it}$ of the stack structure of SiO$_2$/Al$_2$O$_3$ is the same as that of Al$_2$O$_3$ single layer and is also lower than that of SiO$_2$.

Fig. 5. $J-E$ characteristics of GaN MOS capacitors with SiO$_2$, Al$_2$O$_3$ and SiO$_2$/Al$_2$O$_3$. The breakdown field of the stack structure of SiO$_2$/Al$_2$O$_3$ is the same as that of SiO$_2$.

Fig. 6. Charge-to-breakdown $Q_{bd}$ of GaN MOS capacitors with SiO$_2$ and SiO$_2$/Al$_2$O$_3$. The $Q_{bd}$ of the stack structure of SiO$_2$/Al$_2$O$_3$ is the same as that of SiO$_2$.

Fig. 7. Transfer characteristics of AlGaN/GaN hybrid MOS-HFETs with SiO$_2$ and SiO$_2$/Al$_2$O$_3$. The on-state characteristic with stack structure of SiO$_2$/Al$_2$O$_3$ is superior to that with SiO$_2$.

Fig. 8. Field-effect mobility versus channel length of AlGaN/GaN hybrid MOS-HFETs with SiO$_2$ and SiO$_2$/Al$_2$O$_3$. The field-effect mobility with stack structure of SiO$_2$/Al$_2$O$_3$ is higher in all channel length.