Effect of High-k Passivation Layer on High Voltage Properties of GaN Metal-Insulator-Semiconductor Devices

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ABSTRACT In this paper, the GaN-based MIS-HEMTs with Si$_3$N$_4$ single-layer passivation, Al$_2$O$_3$/SiN$_x$ bilayer passivation, and ZrO$_2$/SiN$_x$ bilayer passivation are demonstrated. High-k dielectrics are adopted as the passivation layer on MIS-HEMTs to suppress the shallow traps on the GaN surface. Besides, high permittivity dielectrics passivated MIS-HEMTs also show an improved breakdown voltage characteristic, and that is explained by 2-D simulation analysis. The fabricated devices with high-k dielectrics/SiN$_x$ bilayer passivation exhibit higher power properties than the devices with plasma enhanced chemical vapor deposition-SiN$_x$ single layer passivation, including smaller current collapse and higher breakdown voltage. The Al$_2$O$_3$/SiN$_x$ passivated MIS-HEMTs exhibit a breakdown voltage of 1092 V, and the dynamic $R_{on}$ is only 1.14 times the static $R_{on}$ after off-state $V_{DS}$ stress of 150 V. On the other hand, the ZrO$_2$/SiN$_x$ passivated MIS-HEMTs exhibit a higher breakdown voltage of 1207 V, and the dynamic $R_{on}$ is 1.25 times the static $R_{on}$ after off-state $V_{DS}$ stress of 150 V.

INDEX TERMS AlGaN/GaN, MIS-HEMTs, Si$_3$N$_4$, high-k, Al$_2$O$_3$, ZrO$_2$, current collapse, dynamic on-resistance, breakdown voltage.

I. INTRODUCTION

GaN-based metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs) are expected to be applied in high voltage switching systems, due to their superior characteristics of high critical breakdown field ($\sim 3.5$ MV/cm), large saturation velocity ($\sim 2.5 \times 10^7$ cm$^2$/s), and high electron mobility ($\sim 1500$ cm$^2$/V$\cdot$s) [1]. However, despite promising high power properties of GaN-based devices, the reliability issues induced by the passivation layer under high electric field and dynamic switching are still a major concern. Most of the conventional passivation materials on MIS-HEMTs are SiO$_2$ or SiN$_x$ with relatively low relative permittivity ($\varepsilon_r < 7$), wide band gap ($E_G > 5$ eV) and high critical breakdown field ($E_f \sim 20$ MV/cm) [2], [3]. The low-pressure chemical vapor deposition (LPCVD) of SiN$_x$, has been investigated as the passivation of GaN-based MIS-HEMTs to exhibit decent properties (especially in dielectric breakdown and SiN$_x$/GaN interface) [3]. However, the degradation of ohmic contact electrodes may occur during the high temperature ($\sim 650$ °C) deposition process. The plasma enhanced chemical vapor deposition (PECVD) of SiN$_x$ grown with a faster deposition rate at a lower temperature of $\sim 350$ °C has also long been a common passivation layer for GaN-based MIS-HEMTs [4]. However, the exposure of the GaN surface to the plasma in the PECVD process may cause the degradation of the SiN$_x$/GaN interface, resulting in increased density interface states and leakage currents [5]. The high-k materials deposited by thermal atomic layer deposition (ALD) have been commonly researched as the
gate dielectric on GaN-based MIS-HEMTs, for example, Al\(_2\)O\(_3\) (the relative permittivity \(\varepsilon_r \sim 9\) [6], HfO\(_2\) (\(\varepsilon_r \sim 20\)) [7], ZrO\(_2\) (\(\varepsilon_r \sim 30\)) [8], and TiO\(_2\) (\(\varepsilon_r \sim 55\)) [9]. Those dielectrics possessed excellent characteristics, such as free of plasma-induced damage, high film qualities, and low deposition temperature. The research of applying high-k dielectrics as the passivation layer on the GaN-based devices has recently begun. As one of the premier investigations on the high-k passivation, the reference [10] conducted a 2-D simulation analysis of breakdown characteristics in HEMTs as a function of \(\varepsilon_r\) of the passivation layer. This study found that the off-state breakdown voltage is enhanced when \(\varepsilon_r\) is high. After that, a similar numerical analysis has been performed in the reference [11], which also indicated the breakdown voltage increased as \(\varepsilon_r\) increased. This points out that high-k dielectrics show great potential and advantages as a choice for the passivation layer on GaN-based MIS-HEMTs. Meanwhile, there have been few experimental researches reported the high-k passivation layers’ effect on the high voltage properties of GaN-based MIS-HEMTs. In this study, the electrical properties of AlGaN/GaN MIS-HEMTs with different passivation layers will be investigated on the base of a preliminary study [12]. The high-k dielectrics, Al\(_2\)O\(_3\) and ZrO\(_2\) as the interlayer between GaN cap and PECVD-SiN\(_x\) passivation are considered. The devices with or without high-k dielectrics interlayer will be compared. Reduced dynamic on-resistance and improved breakdown voltage are simultaneously exhibited on the MIS-HEMTs with high-k dielectrics interlayer, indicating a potential of the proposed high voltage devices structure. Furthermore, a TCAD simulation of the electric field in MIS-HEMTs as functions of the relative permittivity of the passivation layer will be performed.

II. DEVICE FABRICATION

The investigated AlGaN/GaN heterostructure epitaxial structure included from top to bottom a 2 nm thick GaN cap layer, a 22 nm undoped Al\(_{0.25}\)Ga\(_{0.75}\)N barrier, a 330 nm GaN channel layer and a 5.1 \(\mu\)m GaN buffer on a Si substrate. The fabrication processes were started from the mesa isolation. Specifically, the mesa isolated region was formed by BCl\(_3\)/Cl\(_2\) inductive coupled plasma etching. Then, the Au-free ohmic contacts were formed with electron beam evaporation of Ti/Al/Ni/TiN (30/120/55/50 nm) metal stack and followed by rapid thermal annealing at 870 \(^\circ\)C in N\(_2\) ambient for 40 s. After organic cleaning processes and a 5 mins HCl surface treatment on the wafer, a 120 nm SiN\(_x\) was deposited as the passivation for sample A. An Al\(_2\)O\(_3\)/SiN\(_x\) bilayer passivation with thicknesses of 22/120 nm was deposited for sample B. A ZrO\(_2\)/SiN\(_x\) bilayer passivation with thicknesses of 22/120 nm was deposited for sample C.

The thickness of dielectrics was measured by using spectroscopic ellipsometry. All the SiN\(_x\) was deposited by PECVD at 350 \(^\circ\)C with a NH\(_3\) flow of 10 sccm, a SiH\(_4\) flow of 13.5 sccm and a N\(_2\) flow of 1000 sccm. The ALD-Al\(_2\)O\(_3\) layer was grown at 230 \(^\circ\)C with a growth rate of 0.11 nm/cycle. H\(_2\)O and Trimethylaluminum (TMA) were used as precursors of oxygen and Al, respectively. The ALD-ZrO\(_2\) layer was grown at 200 \(^\circ\)C with a growth rate of 0.12 nm/cycle. H\(_2\)O and Tetrakis (ethylenediamino) zirconium were used as precursors of oxygen and Zr, respectively. After the dielectrics deposition, the SiN\(_x\) layer in gate regions was removed by reactive ion etching, and the Al\(_2\)O\(_3\) and ZrO\(_2\) layers in gate regions were etched away by a 2% HF solution. A 22 nm ALD-Al\(_2\)O\(_3\) was then deposited as the gate dielectric for three samples. Lastly, Ni/TiN (50/100 nm) metal stack was evaporated as gate electrodes. A schematic cross-sectional view of the three groups of MIS-HEMTs is demonstrated in Fig.1. The fabricated MIS-HEMTs feature a fixed gate-source separation \(L_{SG}\) of 3 \(\mu\)m, gate length \(L_G\) of 3 \(\mu\)m, and gate-drain separation \(L_{GD}\) of 15 \(\mu\)m. The Keysight B1505A power device analyzer was used to measure the electrical properties.

II. RESULTS AND DISCUSSION

Transmission electron microscope (TEM) measurement has been carried out to investigate the cross-section images of the fabricated devices and the cross section TEM micrographs at the passivation region of each sample are shown in Fig. 2. It can be observed that samples with the ALD dielectric interlayer exhibited a sharper passivation/barrier interface morphology.

The DC \(I_D-V_{GS}\) and \(I_G-V_{GS}\) curves of the three samples are plotted in Fig. 3. The transfer characteristics were measured by the gate voltage double-direction sweeping between \(-12\) V and \(6\) V with a step of 100 m, and the drain bias was set as \(10\) V. The threshold voltage are extracted to be \(-9.6\) V, \(-9.5\) V and \(-9.5\) V for samples A, B and C.
respectively, at a drain current criterion of 1 $\mu$A/mm. Samples A, B and C exhibit a low threshold hysteresis ($\Delta V_{th}$) of $\sim 109$ mV, $\sim 106$ mV and $\sim 99$ mV, respectively, and the subthreshold slope (SS) of $\sim 110$ mV/dec, $\sim 101$ mV/dec and $\sim 102$ mV/dec, respectively. The electrostatics characteristics (e.g., $\Delta V_{th}$ and SS) are very similar for the three samples because the gate structures are identical for the three devices. Moreover, the $I_{ON}/I_{OFF}$ ratios of the three samples are calculated to be larger than $1 \times 10^{10}$. The devices B and C with bilayer passivation are well pinched off at $V_{GS} = -12$ V with an off-state drain leakage current of $\sim 100$ pA/mm, indicating the interlayer would not induce the off-state leakage currents in associated with the leakage component through mesa isolation surface [13]. Note that the variation of the $I_D-V_{DS}$ curves for the three samples has not been found obvious, hence the DC output characteristics of samples have been excluded from this paper.

The dynamic on-state performance of the three samples was evaluated by using a pulsed $I_D-V_{DS}$ measurement under fast switching with different quiescent bias points. The schematic timings of voltage signals in current collapse measurements are demonstrated in Fig. 4 (a) [14]. At the off-state, quiescent gate bias ($V_{GS,Q}$) was fixed at $-15$ V and quiescent drain biases ($V_{DS,Q}$) were set as 50 V, 75 V, 100 V, 125 V and 150 V. The off-state stress time was 2 s. The pulsed output curves were measured at 500 $\mu$s after off-state voltage stresses. The ON-state was chosen to feature $V_{GS} = 6$ V. Fig. 4(b) shows the DC and pulsed $I_D-V_{DS}$ curves of the three MIS-HEMTs. The DC $I_D-V_{DS}$ curves before the stresses are used as references (solid lines in black).

Effective suppression of the current collapse effect by the Al$_2$O$_3$/SiN$_x$ passivation is demonstrated with a small difference between the DC and pulsed output curves. Compared with the PECVD-SiN$_x$ passivation, the ALD-dielectrics/SiN$_x$ shows an enhanced dynamic performance with $V_{DS,Q}$ higher than 50 V.

The ratios of dynamic on-resistance ($R_{ON,D}/R_{ON,S}$) of three samples are extracted and plotted in Fig. 5. On-state resistance was extracted from the linear region of the output
curve, and it was chosen to feature $V_{GS} = 6$ V and $V_{DS} = 0.5$ V. A sharp increase of the dynamic $R_{on}$ is observed for the PECVD-SiNx passivated MIS-HEMTs. Specifically, shown as the black line in Fig. 5, the dynamic $R_{on}$ of the SiNx is 1.36 times the static $R_{on}$ when the off-state stress $V_{DS, O}$ is higher than 150 V. By comparison, the dynamic $R_{on}$ of the Al$_2$O$_3$/SiNx and ZrO$_2$/SiNx passivated devices are only 1.14 and 1.25 times the static $R_{on}$ after off-state $V_{DS, O}$ stress of 150 V, respectively. The results point out that the passivation layer with high quality ALD high-k layers could suppress the current collapse effectively. The more significant current collapse effect exhibited in the PECVD-SiNx passivated sample is possibly caused by the plasma damage or failure to eliminate interface states between GaN and passivation [15], [16].

The MIS-capacitors with PECVD-SiNx, ALD-Al$_2$O$_3$ or ALD-ZrO$_2$ as the dielectric have been fabricated to extract the shallow interface state density between the PECVD-SiNx/GaN or between the ALD-oxides/GaN. The thickness of dielectrics is 22 nm for all samples. Multi-frequency C-V characteristic curves of MIS-capacitors are shown in Fig. 6. The measurement gate bias was swept from $-10$ V to 5 V with a step of 50 mV, and the frequency was varied from 2 MHz down to 1 kHz. A large bias voltage could act as electric stress on the gate that would generate more defects at the dielectric/GaN interface and the bulk of the dielectric [17]. Therefore, the maximum gate bias was set as 5 V for the CV measurement to estimate the as-grown interface defects. The C-V curves feature two rising edges. The first rising edge with a smaller frequency dispersion is observed by the PECVD-SiNx film. The obvious horizontal frequency dispersion is detected in the second rising edge for the SiNx/GaN and ZrO$_2$/GaN samples. In the case of SiNx/GaN device, the interface includes very high interface trap density ($D_{it}$), thus the second step at low frequency cannot be observed even at high forward gate bias [18]. The maximum capacitance of the SiNx sample was extracted as 221 nF/cm$^2$. If using the maximum capacitance value to estimate the dielectric constant of the SiNx film, the result would be 5.4 that is significantly lower than its theoretical value ($\sim 7.5$). Moreover, the down-sweep C-V curve at 1 kHz exhibited a much steeper slope at the forward biases (Not shown here). It is speculated that the accumulation capacitance or the second C-V step was not reached in the SiNx sample, due to a high density of traps at the PECVD-SiNx/GaN interface. By contrast, a rising edge with a smaller frequency dispersion is observed by using the Al$_2$O$_3$ as the dielectric. The dielectrics/GaN $D_{it}$ can be calculated by the second slope onset voltage in the multi-frequency C-V curves.

Fig. 7 shows the interface trap density distributions at the dielectrics/GaN interface for the MIS-capacitor structures obtained from the interface state density - energy level mapping method [19]. The means value and the standard deviation of $D_{it}$ was obtained from the interface state density - energy level mapping method [19]. The means value and the standard deviation of $D_{it}$ was obtained from the interface state density - energy level mapping method [19]. The means value and the standard deviation of $D_{it}$ was obtained from the interface state density - energy level mapping method [19]. The means value and the standard deviation of $D_{it}$ was obtained from the interface state density - energy level mapping method [19].
bias of 5 V, the accumulation C-V plateau at forward biases were not shown up. The capacitance of the ZrO$_2$ film was extracted from the ZrO$_2$/Si MOS capacitor structure. For the SiN$_x$/GaN sample, the D$_{it}$ is calculated to be over $3 \times 10^{13}$ cm$^{-2}$eV$^{-1}$ in the energy level range of $\sim 0.38$ eV to $\sim 0.47$ eV from the conduction band, which can be explained by the plasma damage on the exposed GaN surface during the SiN$_x$ deposition. Moreover, the D$_{it}$ at the shallower energy level cannot be calculated by the C-V method, because the second steps at low frequency have not been observed. For the ZrO$_2$/GaN sample, the D$_{it}$ varies from $9.4 \times 10^{12}$ cm$^{-2}$eV$^{-1}$ to $4.7 \times 10^{13}$ cm$^{-2}$eV$^{-1}$, when the energy level depth changes from $\sim 0.28$ eV to $\sim 0.47$ eV. In comparison, the Al$_2$O$_3$/GaN sample shows the lowest D$_{it}$ distribution among the three samples from $1.3 \times 10^{13}$ cm$^{-2}$eV$^{-1}$ down to $8.6 \times 10^{12}$ cm$^{-2}$eV$^{-1}$. It demonstrates that the shallow traps on the GaN surface have been effectively suppressed by the ALD-Al$_2$O$_3$. Lower D$_{it}$ at the dielectrics/GaN interface would have a weak electron trapping effect under quiescent stress. This also supports the suppression of the current collapse effect in the Al$_2$O$_3$/SiN$_x$ passivated devices, as illustrated in Fig. 5.

Fig. 8 demonstrates the off-state breakdown characteristics of MIS-HEMTs at $V_{GS} = -15$ V with the floating substrate. The inserted figure shows the off-state $I_D$ and $I_G$ curves of 11 representative devices for each sample. Sample A passivated by PECVD-SiN$_x$ presents a breakdown voltage of 885 V, Sample B with Al$_2$O$_3$/SiN$_x$ passivation exhibits a breakdown voltage of 1092 V, which were extracted at drain leakage current criterion of 10 uA/mm. By contrast, for sample C with ZrO$_2$/SiN$_x$ passivation, a higher hard breakdown voltage of 1207 V is observed, giving a power figure of merit (BV$^2$/R$_{on,sp}$) of 447 MW/cm$^2$. Note that, the gate leakage current is equal to the drain leakage current for all measured devices, thus $I_D$ and $I_G$ curves are overlapped, as shown in Fig. 8. It indicates that MIS-HEMTs with and without high-k dielectrics exhibited similar off-state drain and gate leakage performance, and the drain to gate leakage current dominated the off-state breakdown of devices.

The 2-D electric field analysis was implemented by using Sentaurus TCAD simulation tools to further explain why the high-k dielectrics passivated devices exhibit a higher breakdown voltage. The gate dielectric is a 20 nm Al$_2$O$_3$. The passivation layer is 100 nm thick and its relative permittivity ($\varepsilon_r$) is set as 4.2, 10, 20 and 30 in the simulation evaluation. The donor concentration in the AlGaN barrier and GaN channel layer is set at a low value of $1 \times 10^{15}$ cm$^{-3}$. The devices are in an off-state, and their dimension is fixed as a 3 $\mu$m $L_{SG}$, a 3 $\mu$m $L_G$, and a 15 $\mu$m $L_D$. Here, we consider a high acceptor density in the GaN buffer layer of $1 \times 10^{17}$ cm$^{-3}$, because a recent research [20] reported that a high acceptor density is required to mitigate the short-channel effects. Fig. 9 plots the electric field (E) profiles along the AlGaN/GaN heterojunction interface at drain biases of 200 V, 400 V and 600 V. When $\varepsilon_r = 4.2$ (in Fig. 9(a)), the increase in $V_D$ is entirely applied along the drain edge of the gate. By contrast, when $\varepsilon_r = 30$ (in Fig. 9(d)), the electric field peak is reduced. The difference in electric fields can be explained by the following: According to Gauss’s law, the electric field across a dielectric is inversely proportional to its relative permittivity with a constant voltage applied. For the devices when the high-k dielectrics passivated on the GaN, the electric field drop becomes weaker from the drain to the gate. Note that, impact ionization effect caused by a high

![FIGURE 8. Off-state breakdown characteristics of the fabricated AlGaN/GaN MIS-HEMTs with PECVD-SiN$_x$ passivation (in black lines), Al$_2$O$_3$/SiN$_x$ passivation (in red lines) or ZrO$_2$/SiN$_x$ passivation (in blue lines). (Inset figure: the off-state breakdown characteristics of 11 representative MIS-HEMTs for each sample).](image-url)

![FIGURE 9. Electric field profiles along AlGaN/GaN interface. (a) $\varepsilon_r = 4.2$, (b) $\varepsilon_r = 10$, (c) $\varepsilon_r = 20$ and (d) $\varepsilon_r = 30$.](image-url)
electric field would lead to the generation of electrons and holes. The generated carriers flow to the electrodes would cause a sudden increase in gate leakage current or drain leakage current [10]. Therefore, the passivation layer with a higher $\varepsilon_r$ can more reduce electric field peak at the drain edge of the gate, then the improvement of gate hard breakdown voltage becomes more significant. A similar phenomenon has also been reported in Ref. [11].

In the actual case, there was a 1 $\mu$m field plate-like hang at the drain side of the gate on the fabricated devices, which was used to avoid the alignment mistake during the photolithography process. Fig. 10 shows a comparison of electric field profiles at the AlGaN/GaN heterojunction interface for a 1 $\mu$m field plate at four cases with $\varepsilon_r=4.2, 10, 20$ and 30. It can be observed that the field plate reduces the electric field peak at the drain edge of the gate significantly and causes a new electric field peak at the terminal of the field plate. In the case of $\varepsilon_r=4.2$ (dashed line in black), the electric fields at the drain-electrode edge as well as at the field-plate edge become very high. By contrast, in the case of $\varepsilon_r=30$ (dashed line in blue), the electric field profiles in these two regions are weaker. It is also indicated that the high-k passivation would not affect the field plates’ function in modulating the electric field. In addition, a more uniform and weaker electric field distribution can be achieved from the drain to the gate for the case with the high-k passivation layer plus the field plate structure.

![Electric field profiles along AlGaN/GaN interface for a field plate length of 1 $\mu$m.](image1)

In Fig. 11, benchmarking of the breakdown voltage versus the specific on-resistance of the three samples were presented and compared with other reported gate recess free GaN based MIS-HEMTs [3]–[5], [21]–[26]. Sample C exhibited a specific on-resistance ($R_{ON,SP}$) of 3.26 m$\Omega$·cm$^2$, taking a 3 $\mu$m transfer length for source and drain ohmic contacts into account. The fabricated AlGaN/GaN MIS-HEMTs with the ZrO$_2$/SiNx passivation in this paper exhibited a satisfactory breakdown characteristic compared with other mainstream reports of GaN-based MIS-HEMTs. Note that, although insertion of the high-k interlayers is capable of improving the high power performances of GaN-based devices, the additional step of ALD is required to be added into the fabrication process, which would increase the costs of devices fabrication. Further works will be focused on growing the high quality high-k dielectrics with a large thickness by using rapid deposition techniques.

IV. CONCLUSION

In summary, the AlGaN/GaN MIS-HEMTs with SiNx single-layer passivation or with high-k dielectrics/SiNx bilayer passivation are demonstrated and compared. The Al$_2$O$_3$/SiNx passivated MIS-HEMTs present a breakdown voltage of 1092 V, and the ZrO$_2$/SiNx passivated MIS-HEMTs present a further high breakdown voltage of 1207 V. Moreover, switching after an off-state $V_{DS, Q}$ stress of 150 V, the current collapse effect of the high-k dielectrics/SiNx passivated devices are significantly suppressed. This points out that the surface traps on GaN can be passivated by the robust ALD dielectrics effectively. The results show a remarkable improvement in the breakdown and dynamic characteristics compared with the PECVD-SiNx passivated MIS-HEMTs. In addition, we have made a 2-D TCAD simulation of electric field profiles in the off-state MIS-HEMTs, where the devices with various relative permittivity of the passivation layer are analyzed. The simulation analysis points out that the high-k passivation is capable of reducing the electric field intensity at the drain edge of the gate in MIS-HEMTs, thus improve the breakdown characteristic. The measured breakdown performance is in accordance with the simulated result, indicating that the breakdown characteristics of MIS-HEMTs
can be improved by increasing the relative permittivity of the passivation layer. This shows a significant potential of employing ALD high-k dielectrics as the passivation layer on the GaN-based devices for high voltage switch applications.

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