AlGaN/GaN Metal-Insulator-Semiconductor High Electron-Mobility Transistor Using a NbAlO/Al₂O₃ Laminated Dielectric by Atomic Layer Deposition

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We investigate the characteristics of AlGaN/GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) with a NbAlO/Al₂O₃ lamination dielectric deposited by atomic layer deposition (ALD) as the gate insulator. A large gate voltage swing (GVS) of 3.96 V and a high breakdown voltage of −150 V for the MIS-HEMT were obtained. We present the gate leakage current mechanisms and analyze the reason for the reduction of the leakage current. Compared with traditional HEMTs, the maximum drain current is improved to 960 mA/mm, indicating that NbAlO layers could reduce the surface-related depletion of the channel layer and increase the sheet carrier concentration. In addition, the maximum oscillation frequency of 38.8 GHz shows that the NbAlO high-k dielectric can be considered as a potential gate oxide comparable with other dielectric insulators.

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AlGaN/GaN-based electron devices are potential candidates for high power and high temperature applications.[1] However, their gate leakage current results in inferior noise characteristics, larger power consumption and smaller gate voltage swing (GVS), and hence degrades the reliability of AlGaN/GaN HEMTs.[2,3] Different gate insulator layers, such as SiO₂,[4] Al₂O₃,[5–7] AlN,[8] and HfO₂,[9] can increase the energy barrier. Thus, they have been employed as one of the possible solutions to tackle the gate leakage problem. For example, an Al₂O₃ layer deposited by using the atomic layer deposition (ALD) method can provide a low interface state and a good passivation effect on AlGaN.[10] Again, a decrease of oxygen-related trap density at the AlGaN surface is observed after the insertion of a thin Al layer between the AlGaN layer and the metal gate.[11] However, using these dielectrics as gate insulators also yields a serious degradation in transconductance.[4] To circumvent this problem, a high-k dielectric lamination layer is employed to provide more efficient gate modulation in metal-insulator-semiconductor HEMT (MIS-HEMT) structures. HfO₂, with a high dielectric constant (20–25), has been studied as a gate dielectric of MIS-HEMTs that presents higher transconductance.[9] However, the crystallization temperature of HfO₂ is only 375°C, which will lead to a reliability problem when HEMTs operate at higher temperatures. Thus in this Letter, we design a structure considering both the temperature stability and the dielectric constant, and fabricate it by the ALD method. Compared with previous work, the thickness of Al₂O₃ is decreased to 2 nm and all characteristics of the device are improved.[11] It is reported that Nb₂O₅ has an excellent thermal stability and is able to remain amorphous when the operating temperature is higher than 1000°C.[12] The bandgap of Nb₂O₅ is only 3.39 eV, which can be improved by Al₂O₃.

Figure 1(a) is the schematic illustration of the structure of AlGaN/GaN MIS-HEMT. The NbAlO/Al₂O₃ laminated dielectric has a fine interface of Al₂O₃ between the AlGaN, and the total dielectric constant was improved by incorporating Nb to Al₂O₃. To improve the insulating property of the dielectric, we used Nb₀.₅Al₀.₅O as the gate dielectric with a bandgap of 8.34 eV and a dielectric constant of 14.5.

The developed device was grown by metal-organic chemical vapor deposition and consisted of a 40-nm undoped nuclear layer, a 2.4-μm undoped GaN layer, a 1.5-nm AlN inserted layer, and a 22-nm undoped Al₉₀.₅Ga₀.₅N barrier layer on a 2-inch sapphire substrate. We used 1.5 nm-AlN as the insert layer for two reasons. First, the AlN insert layer can increase the conduction band discontinuity, thus the piezoelectric polarization effect was enhanced and the 2DEG density increased. Second, the carrier mobility was significantly enhanced using the AlN insert layer. It was a result of alloy disorder scattering reduction due to the suppression of carrier penetration from the GaN...
channel into the AlGaN layer. Hall measurements showed a sheet carrier density of $1.32 \times 10^{13}$ cm$^{-2}$ and an electron mobility of 1568 cm$^2$/Vs. The laminated gate with 2-nm Al$_2$O$_3$ / 10.4-nm Nb$_{0.1}$Al$_{0.9}$O was deposited on half the sample by an F-120 ALD system at 300°C using alternating pulses of Nb(OEt)$_3$, Al(CH$_3$)$_3$, and H$_2$O as the precursors. In order to form ohmic contact, extra etching processes to remove the NbAlO/Al$_2$O$_3$ dielectric layer above the ohmic contacts areas were achieved by reactive ion etch (RIE) etching. The ohmic contacts were fabricated using a Ti/Al/Ni/Au system. These contacts were annealed at 850°C for 40s using rapid thermal annealing in N$_2$ atmosphere. Using Ni/Al for the gate electrode fabrication, devices with a gate length ($L_g$) of 0.5 μm and gate width ($W_g$) of 100 μm were fabricated. The dc measurements were performed on the fabricated devices by using an Agilent 1500 semiconductor parameter analyzer.

Figure 1(b) shows the hysteresis capacitance-voltage ($C-V$) curves of MIS-HEMT and HEMT. The device has a gate length ($L_g$) of 0.5 μm, a gate width ($W_g$) of 100 μm, and a source-drain distance ($L_{sd}$) of 3 μm. (b) High-frequency hysteresis $C-V$ curves for MIS-HEMT and HEMT at 1 MHz. The inset shows a part of the $C-V$ curve from −8.8 to −8.2 V.

Figure 1(a) gives the reverse breakdown and gate leakage current characteristics of the MIS-HEMT and the HEMT. The inset is the gate leakage current. (b) Schematic energy-band diagrams of the MIS structure in reverse bias voltage.

Figure 3(a) gives the reverse breakdown and gate leakage current characteristics of the MIS-HEMT and the HEMT. Figure 3(b) shows the energy-band diagrams of the MIS structure. The data show that a NbAlO/Al$_2$O$_3$ dielectric can reduce the reverse gate leakage current by about three orders compared to traditional HEMTs (Fig. 3(a) inset). The insertion of NbAlO/Al$_2$O$_3$ could elevate the barrier height to $q\varphi_m$, as shown in Fig. 3(b). When a negative voltage is biased on the gate, the number of electrons that reach the conduction-band of AlGaN will decrease. The reason is that they have to move across the higher barrier by thermal emission or field-assisted emission. Thus, the lower gate leakage current is attributed to the large conduction-band discontinuity and the large bandgap of NbAlO/Al$_2$O$_3$.

To illustrate the breakdown voltage of the devices, the current-voltage ($I-V$) characteristics at high reverse voltage of the MIS-HEMT and HEMT were measured and are shown in Fig. 3(a). The breakdown voltage was measured (Fig. 2). From the inset in Fig. 2, we can hardly observe the frequency dispersion. The threshold voltage shift is less than 80 mV between 10kHz to 1 MHz. The small frequency dispersion reflects the high performance in the MIS capacitor and confirms the high quality for NbAlO dielectric films.
voltage is defined as the voltage at which the sloped straight line of the corresponding leakage current intersects the voltage axis, e.g., located at −150 V and −80 V, for MIS-HEMT and HEMT, respectively. The good breakdown voltage characteristic of MIS-HEMT is attributed to the lower gate leakage, as shown in the inset of Fig. 3(a).

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V_{DS} = 10 \text{ V}
\]

**Fig. 4.** Comparisons of the transfer and transconductance characteristics of MIS-HEMT and HEMT at \( V_{DS} = 10 \text{ V} \).

**Fig. 5.** Comparisons of the MIS-HEMT and the HEMT for (a) drain-source currents at \( V_{G} = 0 \text{ V} \) and (b) carrier concentration as a function of depth.

Figure 4 shows the transfer and transconductance characteristics of NbAlO/Al\(_2\)O\(_3\) MIS-HEMT and HEMT fabricated on the same wafer. The maximum transconductances \( g_{m} \) for the MIS-HEMT and the conventional HEMT are 146 and 185 mS/mm, respectively. A large separation of the channel from the gate metal will lead to the reduction of transconductance of MIS-HEMT. Yet, the decrease of \( g_{m} \) is only 21% for MIS-HEMT with total dielectric thickness of 12.4 nm, which is better than the MIS-HEMT with low-k dielectrics.\(^9\) If 12.4 nm Al\(_2\)O\(_3\) is used as gate dielectric, the \( g_{m} \) would be about 113–125 mS/mm, which is lower than the NbAlO/Al\(_2\)O\(_3\) MIS-HEMT of 146 mS/mm because of the lower dielectric constant of Al\(_2\)O\(_3\). We estimate the transconductance of MIS-HEMT using \( g_{m} = \frac{V_{sat}C_{gs}}{L_{G}} \)\(^9\) where \( V_{sat} \) is the electron saturation velocity; \( C_{gs} \) denotes the gate capacitance; and \( L_{G} \) represents the gate length. There are no significant changes of \( V_{sat} \) for MIS-HEMT and HEMT. Therefore, in order to explain the increase of current density, a comparison of drain-source saturation currents at 0 V gate bias \((V_{G})\) is made, as shown in Fig. 5(a). At \( V_{G} = 0 \text{ V} \), the current density in the MIS-HEMT is 268 mA/mm higher than that in the HEMT. This is potentially due to the increase of sheet carrier concentration or carrier mobility in the channel in the samples coated with NbAlO/Al\(_2\)O\(_3\) dielectric. Although the carrier mobility can be improved by using Al\(_2\)O\(_3\) passivation,\(^7\) the variation of carrier mobility can not cause such a large increase of current density, especially under dc operation. Therefore, we suppose that the increase of current density mainly is resulted from the variation of sheet carrier concentration. Carrier concentration as a function of depth can be calculated from the \( C-V \) curve. The curve of \( N_{s} \) versus depth can be calculated by the equation as follows:\(^{[17]}\)

\[
N_{s} = -\frac{1}{q \cdot \varepsilon_{eq} \frac{dC}{dV}} \times \frac{1}{\frac{dC}{dV}}
\]

(4)

where \( N_{s} \) denotes the carrier concentration; \( \varepsilon_{eq} \) is the NbAlO/Al\(_2\)O\(_3\)/AlGaN equivalent permittivity; \( A \) represents the capacitance area; \( C \) is the capacitance of MIS-HEMT or HEMT; and \( V \) is the corresponding voltage.

The carrier concentration as a function of depth is shown in Fig. 5(b). The peak densities for MIS-HEMT
and HEMT are $1.39 \times 10^{20} \text{cm}^{-3}$ and $1.14 \times 10^{20} \text{cm}^{-3}$, respectively. The difference of coordinates of the two peak densities is 13.2 nm, which is slightly less than the dielectric thickness (12.4 nm). However, the data are still encouraging. Furthermore, for both the MIS-HEMT and HEMT, the deviation of the computed peak depth from practical ones is about 2.5 nm. This is due to the use of an ideal dielectric constant of AlGaN in the calculation process. It does not influence the current density analysis. Additionally, the sheet carrier concentration is $6.37 \times 10^{12} \text{cm}^{-2}$ for MIS-HEMT and $5.67 \times 10^{12} \text{cm}^{-2}$ for HEMT, obtained from an integral of the carrier concentration (Fig. 5(b)). The data show the increase of current. The result is consistent with the dielectric layer changing with the electronic density of states at the AlGaN barrier layer surface and reducing with the surface-related depletion of the channel layer. Furthermore, the insulator layer can provide partial passivation of surface states on the AlGaN surface.

![Fig. 6](image)

Fig. 6. Short-current gain $H_{21}$ and unilateral power gain $U$ versus frequency of Al$_2$O$_3$/NbAlO MIS-HEMT on a sapphire substrate. Device is biased at $V_{ds} = 10 \text{V}$ and $V_{gs} = -4 \text{V}$.

The $S$-parameter measurements for the NbAlO/Al$_2$O$_3$ MIS-HEMT are illustrated in Fig. 6. The short-current gain $H_{21}$ and maximum available gain (MAG) are obtained from the $S$-parameter measurement as a function of frequency. Small-signal measurements were conducted employing coplanar probes. $S$-parameters were measured in the frequency range from 10 MHz to 22 GHz by biasing the device at $V_{ds} = 10 \text{V}$ and $V_{gs} = -4 \text{V}$. The cutoff frequency $f_c$ and the maximum oscillation frequency $f_{max}$ on a sapphire substrate are 16.8 GHz and 38.8 GHz, respectively. The $f_c$ of MIS-HEMT is slightly larger than that of HEMT (16.5 GHz). The results indicate that the deposition of NbAlO/Al$_2$O$_3$ has some positive influences on the rf performance of the device. The superior rf performance of NbAlO/Al$_2$O$_3$ MIS-HEMT is attributed to the passivation of the dielectric layer and the screening of the Coulomb scattering of the charged surface defects by the gate-metallization layer.

In summary, we have fabricated an AlGaN/GaN MIS-HEMT with a NbAlO/Al$_2$O$_3$ dielectric. Through a thorough study of the device characteristics, NbAlO/Al$_2$O$_3$ grown by ALD is proven to be an excellent gate dielectric for GaN MIS-HEMT. The present MIS-HEMT exhibits a larger drain current density of 960 mA/mm and a higher breakdown voltage of $-150 \text{V}$ compared with the traditional HEMT. We find that a NbAlO/Al$_2$O$_3$ dielectric could increase the sheet current concentration of the heterojunction channel, which will improve the drain current density compared to traditional HEMT at the same gate bias. In addition, NbAlO/Al$_2$O$_3$ MIS-HEMT shows a large GVS of 3.96 V and a high maximum oscillation frequency of 38.8 GHz. All of these advantages indicate that ALD NbAlO can be considered as a potential gate oxide in AlGaN.

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