AlGaN channel MIS-HEMTs with a very high breakdown electric field and excellent high-temperature performance

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Abstract: We report on AlGaN channel metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs) for the first time. The insulator of 10-nm SiN\(_x\) was deposited by plasma enhanced chemical vapor deposition, which induced a low reverse and forward Schottky leakage. A very high breakdown electric field of 1.8 MV/cm was reached with a gate-drain distance of 2 \(\mu\)m. The breakdown voltage increased non-linearly with the gate-drain distance and reached 1661 V with a gate-drain distance of 20 \(\mu\)m. As temperature increases from 25 to 275°C, the saturation drain current decreases slightly by 20% from 211 to 169 mA/mm and the on-resistance increases only by 24%.

Keywords: GaN HEMTs, AlGaN channel, breakdown, high temperature

Classification: Electron devices, circuits, and systems

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1 Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) are very promising for next-generation high-efficiency power switching devices due to the superior material characteristics like wide bandgap, high electron saturation velocity, and high sheet carrier density [1, 2]. Recently, AlGaN has been introduced as the channel layer so as to obtain a much higher breakdown voltage due to the larger band gap of AlGaN than GaN [3, 4, 5, 6, 7, 8, 9, 10]. T. Nanjo et al. [3] presented the AlGaN channel HEMTs on sapphire for the first time. In addition, AlGaN channel HEMTs on SiC [11] and AlN [7] substrates were also successively fabricated. To promote crystal quality and increase electron mobility of AlxGa1−xN/AlyGa1−yN heterostructure, our research group proposed AlGaN channel HEMTs with a graded buffer layer, which effectively promote the saturation drain current from 218 to 540 mA/mm [9, 10]. Besides, the high-frequency performance of AlGaN channel HEMTs has also been investigated [4, 12]. Noticeably, although GaN MIS-HEMTs with SiN [13], SiO2 [14], HfO2 [15], ZrO2 [16], LaAlO3 [17], etc. as insulators have been proposed to suppress the gate leakage and RF current collapse, enhance breakdown field, and improve interfacial quality, yet AlGaN channel MIS-HEMTs have never been reported.
In this work, we proposed the AlGaN channel MIS-HEMTs for the first time. The material was first grown and characterized, and then the device fabrication process was simply introduced. The AlGaN channel MIS-HEMTs are shown to deliver a significantly suppressed gate leakage current, an enhanced breakdown electric field, and a very stable saturation drain current and on-resistance at elevated temperatures.

2 Material growth and device fabrication

The Al_{0.40}Ga_{0.60}N/Al_{0.18}Ga_{0.82}N heterostructure was grown on a 2-in. c-plane sapphire substrate by metal-organic chemical vapor deposition (MOCVD). As shown in Fig. 1, the presented structure consists of a 180-nm high-temperature AlN nucleation layer, a 1000-nm Al_{0.18}Ga_{0.82}N buffer layer, a 1-nm AlN interlayer, a 22-nm Al_{0.40}Ga_{0.60}N barrier layer, and a 2-nm GaN cap layer. The crystal quality, surface morphology, and square resistance of the samples were characterized by high resolution X-ray diffraction (HRXRD), atomic force microscope (AFM), and Hall measurements, respectively.

The device fabrication commenced with mesa isolation performed by inductively coupled plasma (ICP) etching, followed by source/drain ohmic contacts formation by a rapid thermal annealing of electron beam evaporated Ti/Al/Ni/Au (20/150/50/40 nm) at 830°C for 30 s in N₂ atmosphere. The surface was then passivated by PECVD-grown 60-nm SiNₓ, followed by gate window open by reactive ion etching (RIE). Afterwards, the 10-nm SiNₓ insulator was deposited by PECVD at 250 °C. The Gate electrodes were then defined by photolithography with a gate width of 50 µm, gate length of 1 µm, source-gate spacing of 1 µm, and gate-drain space of 2 to 20 µm.

3 Material characterization and discussion

Fig. 2 shows the 2D (2-dimensional) and 3D (3-dimensional) AFM images of the Al_{0.40}Ga_{0.60}N/Al_{0.18}Ga_{0.82}N heterostructure. The root mean square (RMS) obtained is 0.304 nm. Suffering from the low adatom diffusion of Al, the crystal quality of
the Al$_{0.40}$Ga$_{0.60}$N/Al$_{0.18}$Ga$_{0.82}$N epitaxial layer was poor [18]. There are no clear step flows but many V-pits in the AFM images, which means the low adatom diffusion of Al have induced a poor crystal quality and surface morphology. By introducing a composite AlGaN/GaN buffer layer, the surface morphology and crystal quality of Al$_{0.40}$Ga$_{0.60}$N/Al$_{0.18}$Ga$_{0.82}$N heterostructures could be effectively promoted [9, 10].

Fig. 3(a) plots the high resolution XRD (0002) $\omega$-2$\theta$ scan of the Al$_{0.40}$Ga$_{0.60}$N/Al$_{0.18}$Ga$_{0.82}$N heterostructure. The Al$_{0.18}$Ga$_{0.82}$N, Al$_{0.40}$Ga$_{0.60}$N, and AlN peaks are clear. Fig. 3(b) demonstrates that the (0002) and (10-12) full widths at half maximum (FWHMs) of the Al$_{0.40}$Ga$_{0.60}$N/Al$_{0.18}$Ga$_{0.82}$N heterostructure are 98 and 1156 arcsec, respectively.

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4 Device characterization and discussion

Fig. 4(a) shows the output characteristics of the AlGaN channel MIS-HEMTs. The saturation drain current at $V_{GS} = 4$ V is 211 mA/mm, due to the low electron mobility of 780 cm$^2$/V·s and low sheet carrier density of $6.9 \times 10^{12}$ cm$^{-2}$. Fig. 4(b) shows the transfer, gate leakage, and transconductance characteristics of the AlGaN channel MIS-HEMTs. The off-state leakage is dominated by gate leakage and the transconductance just reaches 59 mS/mm due to the low electron mobility.
Compared with the traditional AlGaN channel HEMTs without gate insulator, the AlGaN channel MIS-HEMTs exhibits greatly suppressed leakage current \( I_G \) at forward bias region and the leakage current at reverse bias region is also reduced by one order in magnitude (Fig. 5(a)). Fig. 5(b) shows the buffer leakage current of the AlGaN channel MIS-HEMTs. Four devices at different regions on the wafer are measured and buffer leakage currents are around \( 10^{-6} \) A at 100 V.

The three-terminal OFF-state breakdown characteristics of the AlGaN channel MIS-HEMTs with \( L_{GD} \) of 2 µm and 20 µm are depicted in Fig. 6(a) and (b), respectively. Due to the suppressed gate leakage and enhanced electron confinement, the breakdown voltage of the AlGaN channel MIS-HEMTs with \( L_{GD} \) of 2 µm reaches 359 V, which means the average breakdown electric field reaches a very high value of 1.8 MV/cm. As shown in Fig. 6(c), the breakdown voltage increases non-linearly with \( L_{GD} \). As the \( L_{GD} \) increases from 2 µm to 20 µm, the average breakdown electric field gradually decreases from 1.8 MV/cm to 0.83 MV/cm. In fact, when the \( L_{GD} \) is short, the reverse gate bias can easily deplete the channel layer and the buffer layer underneath, thus leading to a very high average break-
down electric field. However, as the $L_{GD}$ gradually increases, the reverse gate bias cannot fully deplete the channel layer and the buffer layer near the drain edge, inducing a reduced average breakdown electric field [2].

Fig. 6. OFF-state breakdown characteristics of the AlGaN channel MIS-HEMTs at $V_{GS} = -5$ V with $L_{GD}$ of (a) 2 µm and (b) 20 µm. (c) Breakdown voltage of the AlGaN channel HEMTs with $L_{GD}$ ranging from 2 to 20 µm. The inset shows the breakdown electric field of the devices.

Fig. 7. (a) Output characteristics with $V_{GS}$ from 1 to 4 V and (b) normalized drain current $I_D$ and (c) normalized on-resistance $R_{on}$ of the AlGaN channel MIS-HEMTs at temperatures from 25 to 275 °C.
Fig. 7(a) shows the output characteristics with $V_{GS}$ from 1 to 4 V at temperatures from 25 to 275°C. The saturation drain current $I_D$ decreases slightly by 20% (Fig. 7(b)) from 211 to 169 mA/mm and the on-resistance $R_{on}$ increases only by 24% (Fig. 7(c)), as temperature increases from 25 to 275°C. In contrast, the $I_D$ of traditional GaN channel HEMTs generally decreases by 50%~70% in this situation [19, 20]. The excellent high-temperature stability of AlGaN channel HEMTs mainly stems from the stable electron mobility at elevated temperatures [9]. Besides, the stable $R_{on}$ is very beneficial to high-temperature and high-power switching application.

5 Summary

In summary, AlGaN channel MIS-HEMTs with 10-nm SiNx as the insulator were successfully fabricated for the first time. The presented devices exhibit a suppressed gate leakage current at both reverse and forward gate bias. The breakdown voltage increases non-linearly with the $L_{GD}$ and reaches 1661 V with $L_{GD}$ of 20 µm. The average breakdown electric field even reaches 1.8 MV/cm with $L_{GD} = 2$ µm, which is quite meaningful to push the breakdown electric field of HEMTs to the ideal GaN breakdown strength of 3.3 MV/cm and to decrease the size of devices. The excellent high-temperature stability of $R_{on}$ is very promising for high-power and high-temperature switching applications.

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