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AlN/GaN HEMTs with high-κ ALD HfO$_2$ or Ta$_2$O$_5$ gate insulation

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AlN/GaN Metal-Insulator-Semiconductor High Electron Mobility Transistors (HEMTs) have been grown and fabricated which utilize a 6 nm thick atomic layer deposited film of either Ta$_2$O$_5$ or HfO$_2$ for gate insulation. Drain, transfer, and gate current characteristics are compared between both structures, showing a measurable difference in threshold voltage and transconductance. The cause is highlighted by the results of capacitance-voltage analysis which showed 10 MHz dielectric constants of 8.7 and 11.7 for the HfO$_2$ and Ta$_2$O$_5$ films, respectively. Furthermore, interface trap state density was extracted by Terman's method and compared between films. Small signal frequency performance of sub-micron gate length HEMTs was representative of the different gate lengths. Consideration of the compared electrical results suggests that at this stage in ALD development, Ta$_2$O$_5$ appears better suited for gate insulation of AlN/GaN HEMTs.

1 Introduction High-frequency transistor technologies are invariably striving toward downscaled geometries in an effort to increase operational frequencies. In addition, GaN-based high electron mobility transistors (HEMTs) have ushered in the capability of a higher operational voltage range owing to their high intrinsic breakdown field strength. The ultra-thin barrier AlN/GaN HEMT offers advantages in both sectors providing a potential avenue for ultra-scaled geometries which can operate at high bias voltage. Furthermore, the AlN/GaN HEMT has demonstrated the capacity to support 2D electronic charge densities up to ~ 6 x 10^{13} cm^{-2} for an AlN barrier thickness of only 5 nm due largely to the large conduction band discontinuity and piezoelectric component of the polarization charge [1]. Such high achievable 2DEG density has enabled drain current densities of up to 2.3 A/mm [2]. Small signal frequency performance from the AlN/GaN HEMT has exceeded 100 GHz [3]. One caveat to this heterostructure is that such a thin barrier prevents the use of Schottky gates due to the propensity of large tunnelling currents. Therefore, a gate insulator is necessary [4]. An assortment of dielectrics have been previously explored.
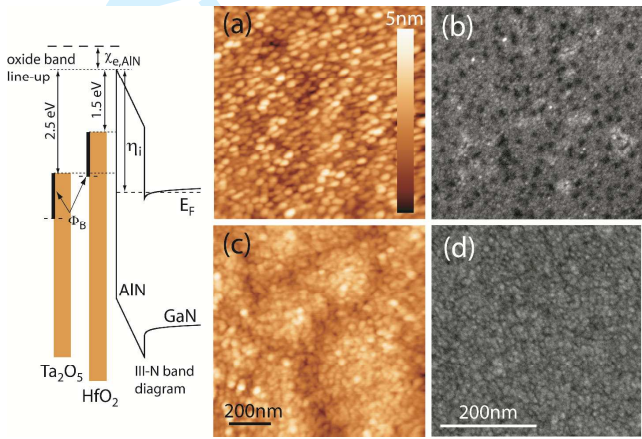

Figure 1 Oxide band line-up relative to the AlN/GaN band diagram (left) using values taken from ref. [14], and 1x1 μm^2 AFM (a - HfO$_2$) and (c – Ta$_2$O$_5$) and SEM (b – HfO$_2$) and (d – Ta$_2$O$_5$) micrographs of the oxide surfaces.

These include Cat-CVD SiN, in-situ MOCVD SiN, atomic layer deposited (ALD) Al$_2$O$_3$, and HfO$_2$, amongst others [4-8]. It is unclear at this point whether there is a dielectric

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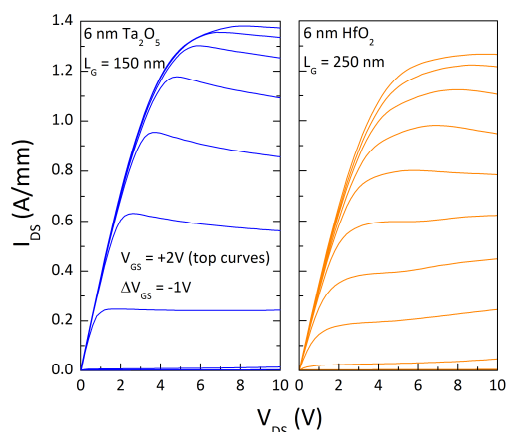
Figure 2 Drain characteristics for the Ta_2O_5/AlN/GaN (left) and the HfO_2/AlN/GaN (right) HEMTs.

Figure 3 Transfer characteristics (left) and gate current characteristics (right).

that is superior for the specific application of gate insulation to the AlN/GaN. This work seeks to compare two commonly available high-κ ALD dielectrics, HfO_2 and Ta_2O_5, through the fabrication of same-wafer, depletion-mode AlN/GaN HEMT devices. A battery of microscopic and electrical characterization was performed to quantify and compare the individual assets of each insulating film.

2 Sample growth and processing III-N epitaxial layers were grown by plasma assisted MBE on a 2-inch semi-insulating 6H-SiC substrate using procedures similar to those described previously [9]. A 60 nm AlN nucleation layer was grown, followed by a 1 µm GaN buffer and a 3.5 nm AlN capping layer. The AlN cap thickness was chosen on the basis of work by Cao and Jena who showed a minimum in sheet resistance for AlN thicknesses between 3 - 4.5 nm [1]. All layers were grown without interrupts or doping and at a substrate temperature of 730 °C. Device processing followed conventional III-N techniques. Prior to 150 and 250 nm long e-beam gate definition, the HfO_2 and Ta_2O_5 dielectrics were deposited using a blanket ALD process in a flow type hot-wall reactor [10]. For the HfO_2 film the precursors were tetrakis ethylmethyl amino hafnium (TEMAHf) and H_2O and the depositions were performed at 250 °C. For the Ta_2O_5 process the precursors were pentakis dimethyl amino tantalum (PDMAT) and H_2O and the depositions were also performed at 250 °C. For both processes a constant 15 sccm ultra high purity N_2 flow was used to maintain the reactor base pressure at 200 mtorr. The purge time between successive precursor and H_2O pulses was set at 30 s for both processes. ALD processes were optimized with regard to temperature, precursor delivery and purge times and the deposition conditions were chosen so that the films were grown in the ALD self-limiting regime. Spectroscopic ellipsometry measurements on native oxide Si witness samples indicated a film growth rate of 1.2 Å/cycle for HfO_2 and 0.6 Å/cycle for Ta_2O_5. Atomic force microscopic (AFM) images of the films deposited on the AlN surface are shown in Figure 1. RMS
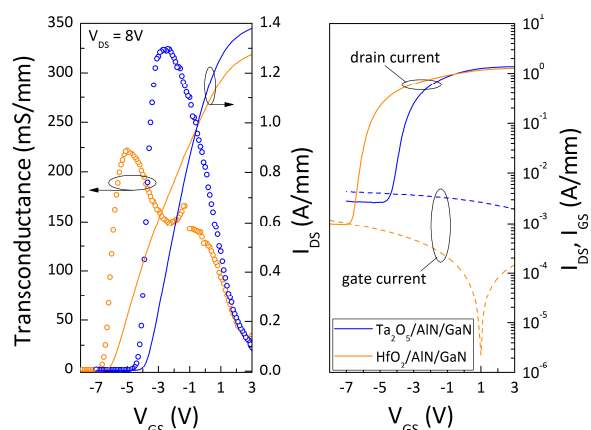
roughness of the HfO_2 and Ta_2O_5 films were 0.98 nm and 0.58 nm, respectively showing a minimal surface roughening from the as-grown AlN surface (0.45 nm RMS roughness).

3 Results and discussion On-wafer, room temperature Hall effect measurements were taken before and after the oxide depositions and the post-processing sheet resistance for the HfO_2 and Ta_2O_5 were 385 Ω/□ (n_s = 2.18 x 10^{13} cm^{-2}, μ = 750 cm^2/Vs) and 356 Ω/□ (n_s = 2.2 x 10^{13} cm^{-2}, μ = 800 cm^2/Vs), respectively. Due to the conformal oxide deposition, partial surface passivation was achieved. This resulted in the enhancement of the 2D charge density by ~10% for both samples after ALD.

Drain, transfer, and capacitance-voltage (C-V) measurements were carried out at room temperature for electrical comparison of both devices and the corresponding characteristics are shown in Figures 2, 3, and 4, respectively. Maximum drain current densities of 1.3 – 1.38 A/mm at V_{GS} = +2V were measured. Off-state breakdown voltages of the HfO_2 and Ta_2O_5 insulated HEMTs were 20 V and ~ 90 V, respectively (not shown). A noticeable difference in peak transconductance was measured between samples with differing films (Figure 3) where the Ta_2O_5/AlN/GaN HEMTs achieved a higher transconductance value of ~ 325 mS/mm, presumably due to its higher dielectric constant of 11.7 compared to 8.7 for the HfO_2 film. This is also reflected in the Ta_2O_5 device's lower threshold voltage. Dielectric constant values were found by fitting C_{max} of the C-V curves at 10 MHz (Figure 4).

Gate current densities of the biased devices are also shown in Fig. 3 and demonstrate leakage current of I_G ~ 1 – 2 mA/mm in subthreshold (V_{GS} = -7 V) for both ALD films. The off-state gate current may be further reduced by the improvement in film roughness (shown in the AFM and SEM images in Figure 1), which suggests some variation in oxide thickness below the gate metal for these extremely thin oxide layers. Similar roughness has been
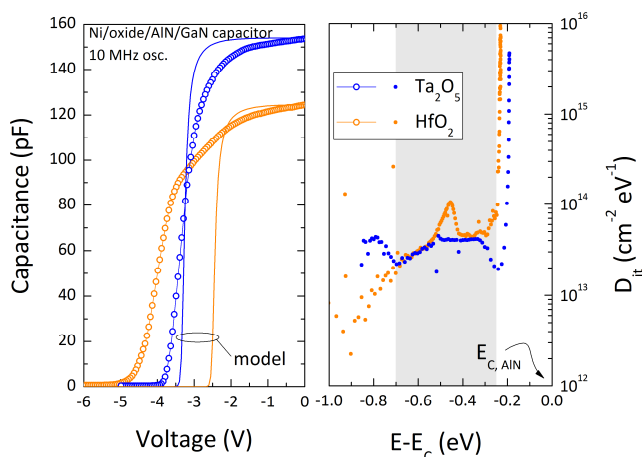
Figure 4 Capacitance-voltage characteristics (left) and extracted interface state density (right).

observed when deposited on Si surfaces as given in ref. [11]. Further work is currently underway to lower gate leakage current by pre-deposition surface treatment, understanding nucleation kinetics, as well as post-deposition annealing of the ALD films.

C-V measurements of the HfO$_2$/AlN/GaN structure showed an irregular depletion characteristic which correspondingly showed up in the transfer and subsequently the twin-peaked transconductance characteristic (Figure 3). This C-V stretch out characteristic is speculated to be due to interfacial traps at the oxide/AlN interface, specific to the oxide involved [12]. In order to investigate this hypothesis, Terman's high-frequency C-V method [13] has been modified for these insulated heterojunction capacitors. Corresponding band offsets shown in the illustration in Fig. 1 were taken from work by Robertson [14]. Interface trap state density (D$_{it}$) was determined by the derivative of the difference between the modeled "ideal" C-V curve and the measured one. The relationship is given by D$_{it}$ = (C$_{ox}$/qk$_B$T)$\partial \Delta V_{GS}/\partial \eta_i$, and is similar in form to the classic result given by Terman. $\Delta V_{GS} = V_{GS,meas} - V_{GS,ideal}$ is the voltage comparison at common capacitance, C$_{ox}$ is the capacitance associated with the oxide layer normalized to area, and η_i is the potential energy at the oxide/AlN interface normalized to k$_B$T. This interface is where the traps are anticipated to reside. The interface potential, η_i, may be determined by the 1D Poisson equation applied along a vertical section of the layer structure below the gate. Single sub-band population was assumed in the derivation of D$_{it}$ which may cause some error in the calculation of the energy range when high 2DEG densities are achieved. Band gap shrinkage of the AlN barrier [1] was not accounted for which could subsequently cause overestimation of the AlN/GaN conduction band offset, also affecting the corresponding energy range of the D$_{it}$ spectra.

Near band-edge interface trap density was extracted and shown in Figure 4. The abrupt increase in D$_{it}$ near band edge is attributed to the asymptotic behavior of the C-V

curves in accumulation which makes ΔV_{GS} erroneously increase and is therefore disregarded in the analysis. The same occurs for deep depletion in the measured data, which causes the D$_{it}$ spectrum to become noisy at lower energy. Thus, the grey region in Figure 3 is taken as the window of validity. Trap density spectra for both films were comparable with a range of $2 - 4 \times 10^{13}$ cm^{-2} eV^{-1}. The anomalous twin-peaked transconductance, a result of the transfer characteristic, and C-V stretch-out of the HfO$_2$-insulated structure verified by a well defined peak in D$_{it}$ ($\sim 10 \times 10^{13}$ cm^{-2} eV^{-1}) at 0.46 eV from the AlN conduction band. It is unclear, at this point, the origin of this energy level and warrants further investigation.

Terman's method inherently probes interface trap states with time constants slower than that of the ac perturbation frequency. Thus, "fast" state charging is not accounted for by this C-V technique. Small signal unity current gain frequencies (f$_t$) of HEMTs using either film were measured. For the HfO$_2$-insulated device extrinsic (no de-embedding) f$_t$ was 35 GHz (L$_G$ $\sim$ 250 nm), and for the Ta$_2$O$_5$-insulated device extrinsic f$_t$ was 49 GHz (L$_G$ $\sim$ 150 nm). These results indicate that the extracted D$_{it}$ has no deleterious effect on HEMT small signal frequency performance.
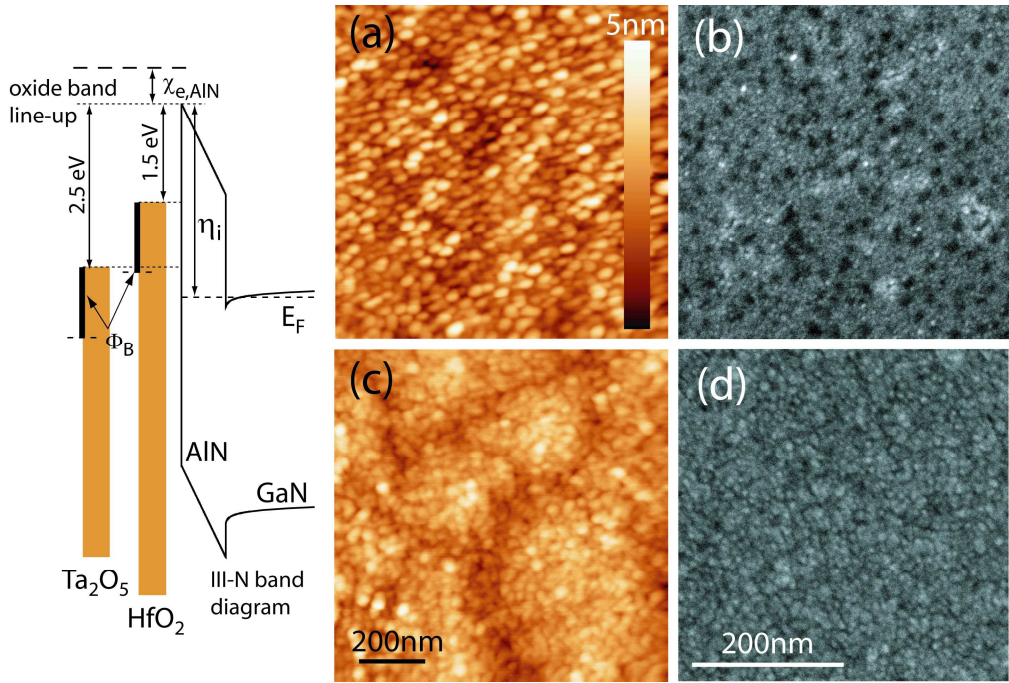
4 Summary Depletion mode insulated-gate AlN/GaN HEMTs have been grown and fabricated utilizing two different high-κ ALD dielectrics (HfO$_2$ and Ta$_2$O$_5$). Devices were characterized by several microscopic and electrical techniques in order to compare the individual benefits of both ALD films on device performance. C-V measurements allowed the extraction of dielectric constant and interface trap density through Terman's method ($\sim 10^{13}$ cm^{-2} eV^{-1}). A well defined trap state was observed for the HfO$_2$-insulated structure which provides an explanation for the anomalous depletion character of the transfer characteristic. Small signal frequency performance was found to follow the respective gate length and showed no deleterious RF result due to the extracted D$_{it}$. Despite considerations of the oxide band line-up to the AlN/GaN heterostructure, it appears at this stage in ALD film development, Ta$_2$O$_5$ is better suited for gate insulation of the AlN/GaN HEMT based on measured characteristics.
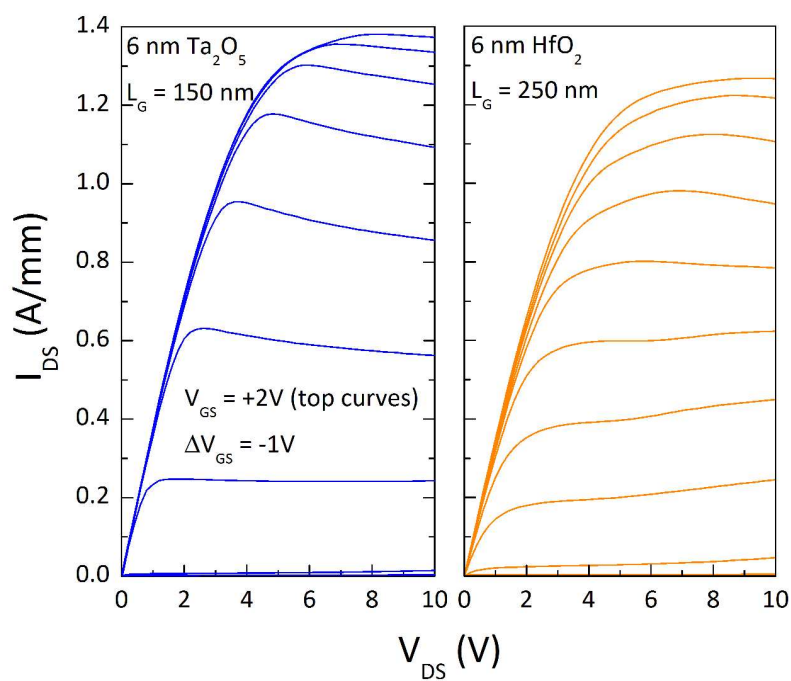
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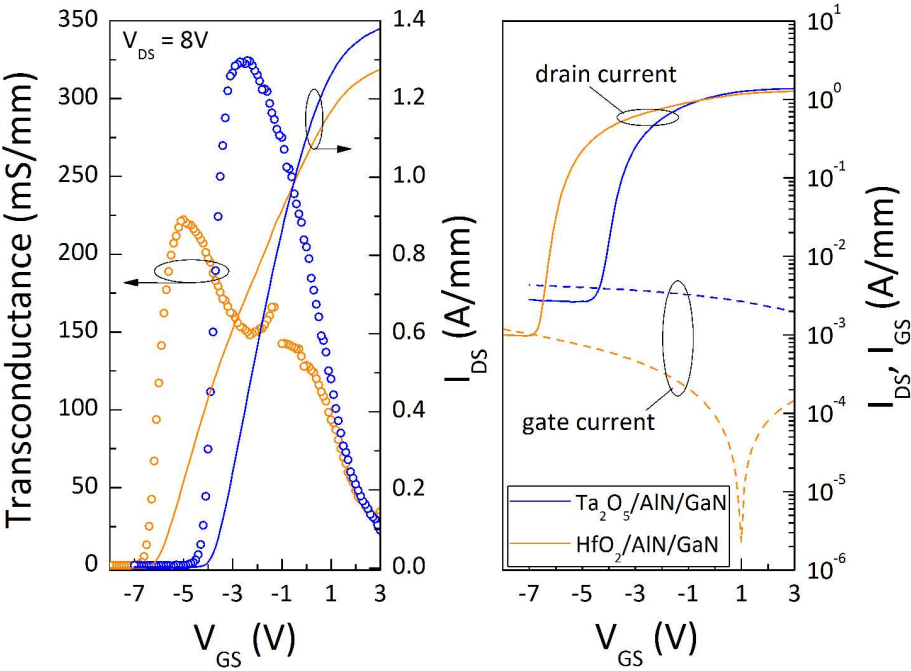[5] M. Higashiwiaki, T. Mimura, T. Matsui, IEEE Elec. Dev. Lett. 9, 27 (2006).

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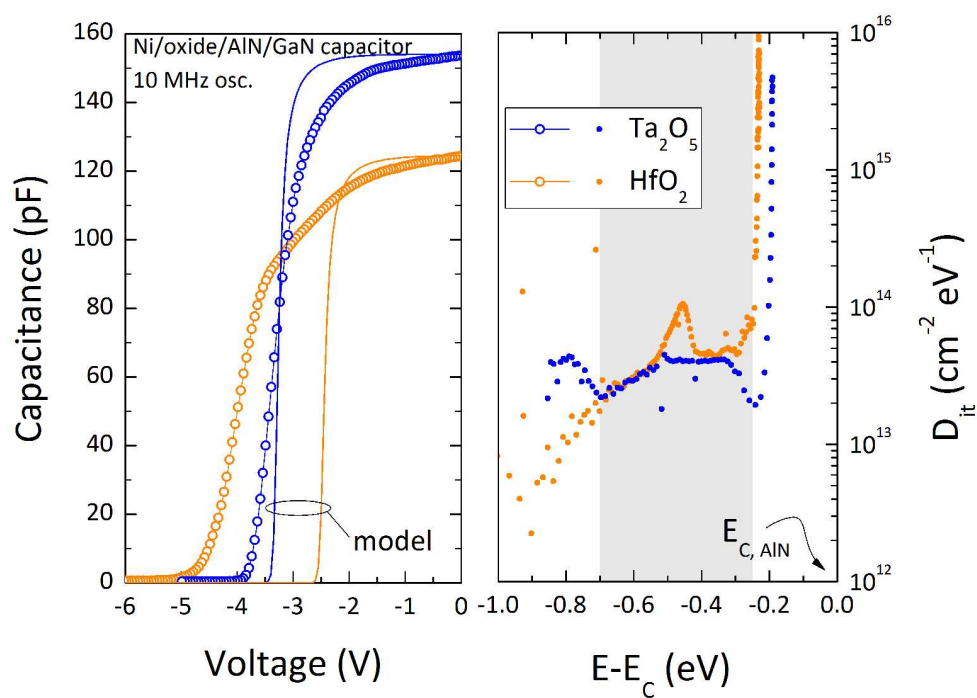[14] J. Robertson and B. Falabretti, J. Appl. Phys. 100, 014111 (2006).

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Drain characteristics for the Ta2O5/AlN/GaN (left) and the HfO2/AlN/GaN (right) HEMTs.

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