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A study of the impact of in-situ argon plasma treatment before atomic layer deposition of Al_2O_3 on GaN based metal oxide semiconductor capacitor

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ABSTRACT

The impact of subjecting a n-GaN surface to an in-situ argon plasma in an atomic layer deposition (ALD) tool immediately before deposition of an Al_2O_3 dielectric film is assessed by frequency dependent evaluation of Al_2O_3/GaN MOSCAPs. In comparison with a control with no pre-treatment, the use of a 50 W argon plasma for 5 min reduced hysteresis from 0.25 V to 0.07 V, frequency dispersion from 0.31 V to 0.03 V and minimum interface state density (D_{it}) as determined by the conductance method from 6.8×10^{12} cm^{-2} eV^{-1} to 5.05×10^{10} cm^{-2} eV^{-1}.

1. Introduction

To suppress gate leakage current in GaN-based power electronic transistors, the incorporation of high-k dielectrics such as Al_2O_3, HfO_2 and ZrO_2 deposited using atomic layer deposition (ALD) in the gate stack have been studied [1–4]. Issues associated with trapped charge at the dielectric to GaN or AlGaN interface have been observed however, along with threshold voltage (V_{th}) instabilities. To address these issues, there have been a number of recent reports on the impact of wet and dry cleans prior to dielectric deposition [5–7]. To date there has been no report on the impact of subjecting a GaN surface to an Ar plasma in-situ in the ALD deposition chamber immediately prior to Al_2O_3 deposition, which is the subject of the work reported here.

The impact of this approach is assessed by frequency dependent capacitance–voltage (C–V) and conductance–voltage (G–V) characteristics in terms of hysteresis, frequency dispersion and interface state density (D_{it}) at the Al_2O_3/GaN interface.

2. Experimental procedure

The GaN MOSCAP structure was grown on a 6″ diameter silicon wafer by MOCVD. The complete layer structure, from the silicon substrate up shown in Fig. 1, comprises; a 0.22 μm AlN nucleation layer, a 0.85 μm undoped graded AlGaN layer, a 1.1 μm 1×10^{18} cm^{-3} Si doped GaN layer to facilitate the formation of a low resistance ohmic contact as the bottom plate of the MOSCAP, and a 0.6 μm 1×10^{17} cm^{-3} Si doped GaN layer. The low conductivity of the AlN nucleation layer necessitated the use of a planar MOSCAP structure whose fabrication began with the deposition of a Ti/Al/Ni/Au ohmic metallization which was annealed at 770 °C for 30 s in N_2 atmosphere to form a low resistance path to the 1.1 μm 1×10^{18} cm^{-3} Si doped GaN layer in the epi-structure. Prior to being introduced into the Al_2O_3 growth chamber, samples were cleaned using organic solvents. Before ALD deposition of Al_2O_3, samples were subjected to a 5 min Ar plasma treatment in-situ in the ALD chamber at plasma powers of 50 W, 150 W and 300 W. After the pre-treatment, 20 nm Al_2O_3 was deposited at 200 °C using a trimethyl-aluminum (TMA) precursor. It has been shown before that dosing the compound semiconductor with TMA first results in self-cleaning, which can remove contaminants before the onset of the dielectric growth occurs [8]. Following ALD

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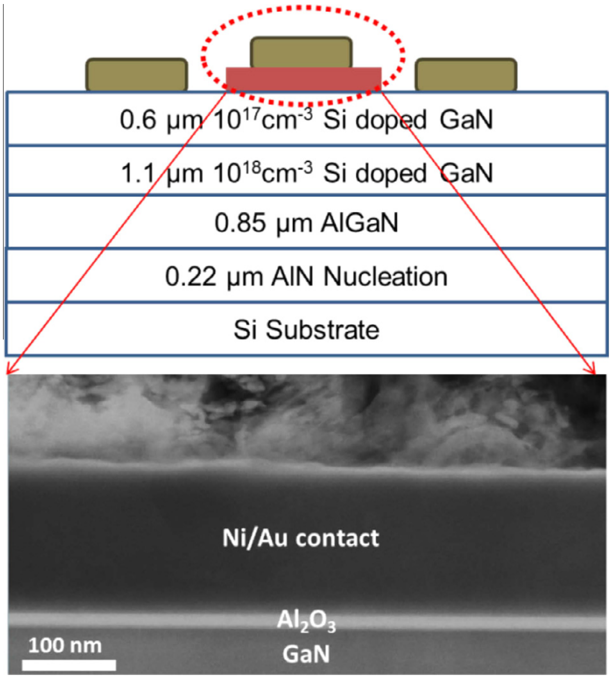

Fig. 1. Schematic cross section of GaN based MOSCAP and TEM cross sectional image.

deposition, windows were opened in the Al_2O_3 layer by reactive-ion etching using $SiCl_4$ gas to facilitate probing to the ohmic contact. A 20/200 nm Ni/Au metallization was then deposited to form the gate contact of the MOSCAP.

Finally, post metal annealing in forming gas for 30 min at 430 °C was performed. Fig. 1 shows a cross section TEM image of a typical n-GaN based MOSCAP.

3. Results and discussion

Fig. 2 shows typical room temperature 1 MHz *C–V* characteristics. The gate voltage was swept from inversion to accumulation and backward to the inversion region. All Ar pre-treated samples showed reduced hysteresis, indicative of an improvement in the Al_2O_3/GaN interface.

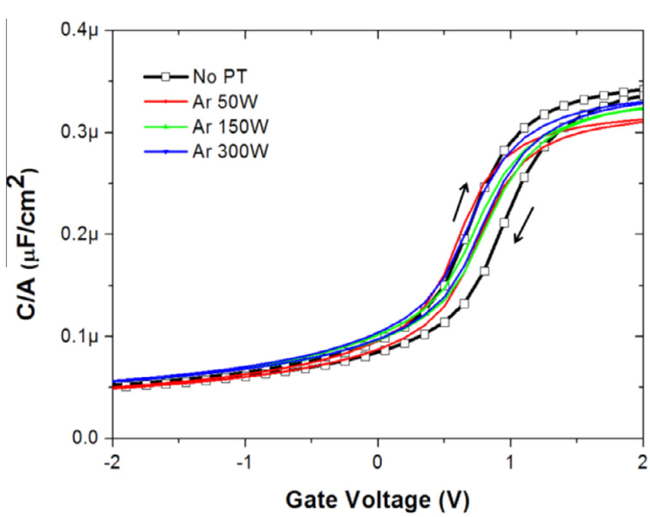

Fig. 2. Hysteresis *C–V* characteristics measured at 1 MHz.

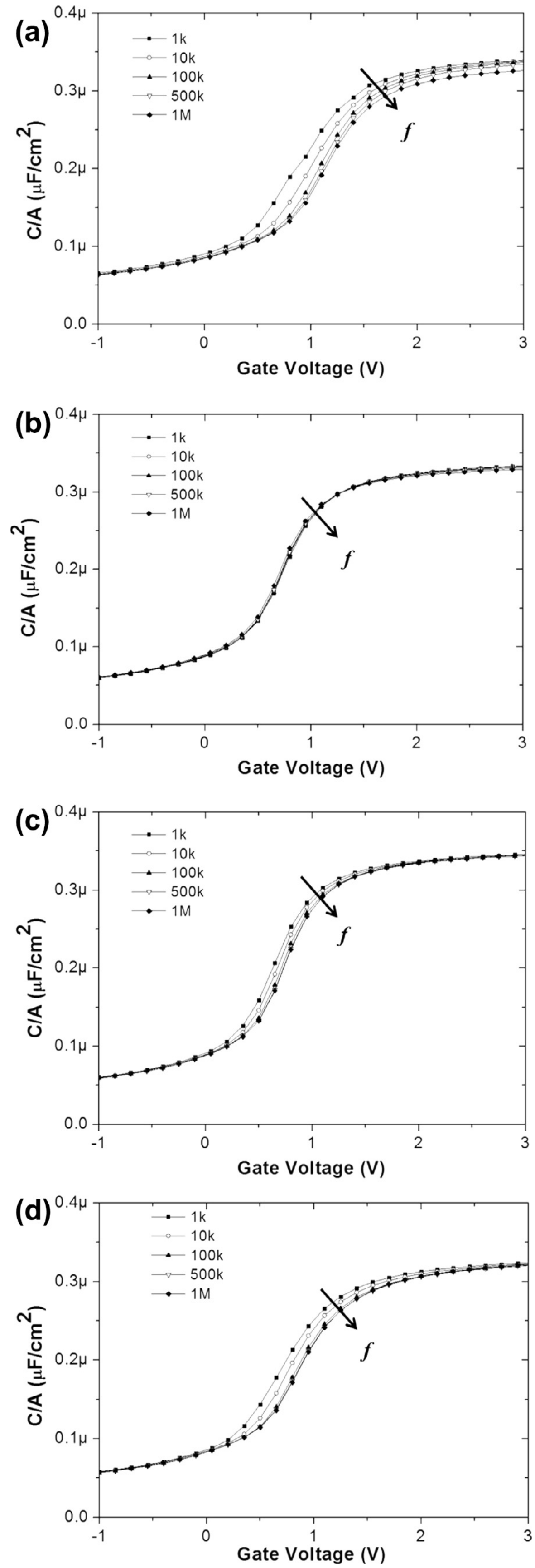

Fig. 3. *C–V* characteristics measured at frequencies from 1 kHz to 1 MHz (a) without treatment, (b) 50 W Ar, (c) 150 W Ar and (d) 300 W Ar plasma treatment.

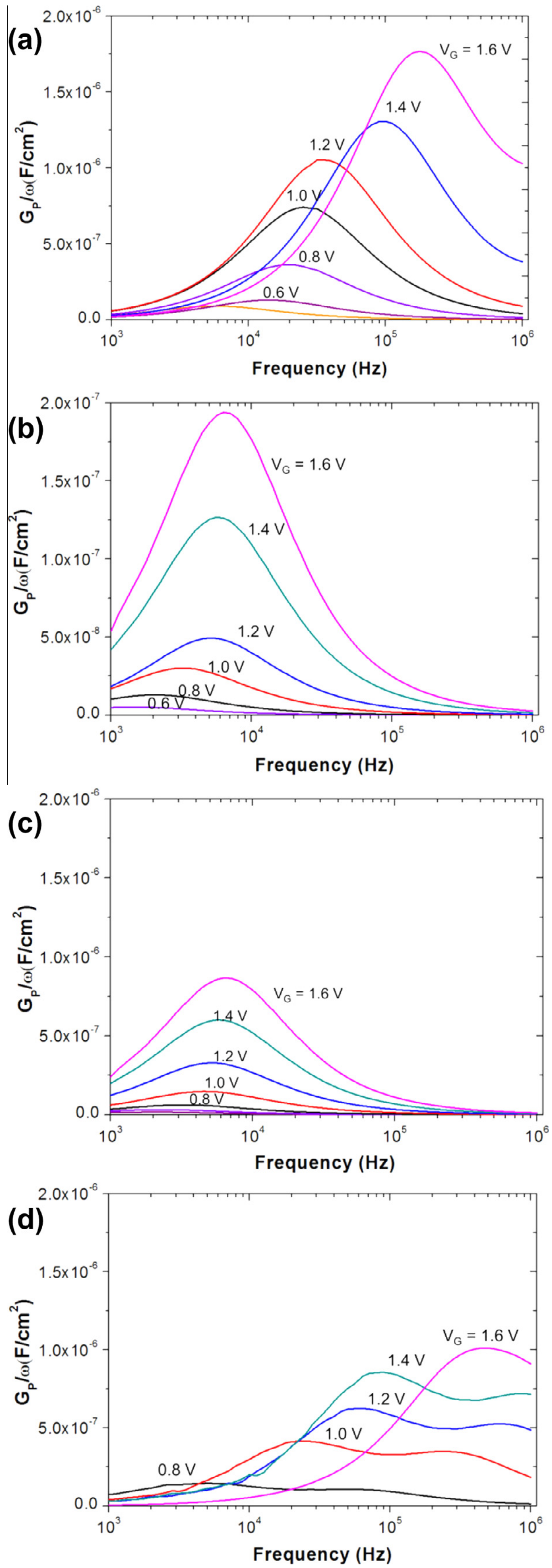

Fig. 4. G_P/ω as a function of gate voltage determined by the conductance method for (a) without treatment, (b) 50 W Ar, (c) 150 W Ar and (d) 300 W Ar plasma treatment.

Table 1
Summary of electrical properties of ALD Al_2O_3 on GaN MOSCAP with different Ar pre-treatments.

	w/o PT	50 W Ar	150 W Ar	300 W Ar
T_{ox}[a] (nm)	20.3	20.5	19.2	19.7
C_m[b] @ 5 V, 1 MHz (μF/cm^2)	0.34	0.34	0.35	0.34
Hysteresis (ΔV)	0.25	0.07	0.08	0.11
Frequency dispersion (ΔV)	0.31	0.03	0.07	0.17
D_{it} (10^{11} cm^{-2} eV^{-1})	68.04	0.50	2.13	22.63

[a] Oxide thickness by ellipsometer.
[b] Measured total capacitance density.

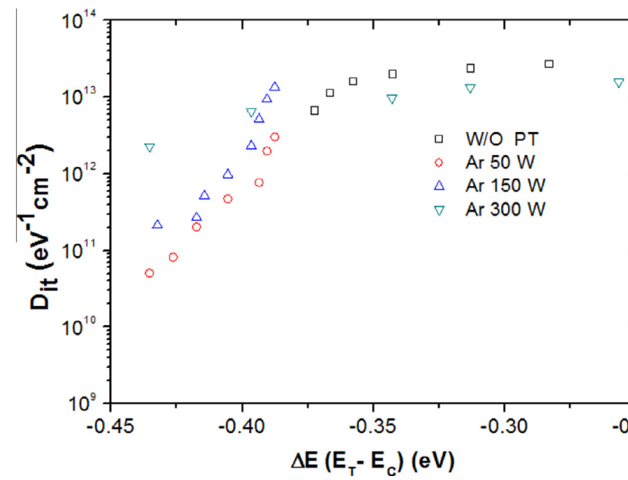

Fig. 5. D_{it} as a function of trap energy level determined by the conductance method for various in-situ Ar pre-treatments.

Fig. 3 shows C–V characteristics of the Al_2O_3/GaN capacitors with the various in-situ Ar plasma treatments measured at frequencies from 1 kHz to 1 MHz at room temperature. The 50 W Ar pre-treated sample demonstrates the lowest frequency dispersion, which suggests that a suitably optimised Ar pre-treatment may reduce D_{it}.

For each sample, the frequency dependent conductance method was used to extract values for D_{it} as a function of gate voltage from the measured capacitance (C_m) and conductance (G_m) via the equivalent parallel conductance (G_P) using

$$\frac{G_P}{\omega} = \frac{\omega G_m C_{ox}^2}{G_m^2 + \omega^2 (C_{ox} - C_m)^2} \tag{1}$$

$$D_{it} \approx \frac{2.5}{q}\left(\frac{G_P}{\omega}\right)_{\max} \tag{2}$$

where C_{ox} is the oxide capacitance [9]. Fig. 4 shows parallel conductance as a function of frequency for the various samples. D_{it} was evaluated from the G_P/ω maxima as a function of gate voltage. The sample pre-treated with 50 W Ar has the lowest D_{it} values over the complete gate bias range.

Trap energy level position (E_T) conduction band (E_C) edge was determined from the frequency (f_{max}) at which G_P/ω has the peak value using

$$E_T - E_C = k_B T \ln\left(\frac{2\pi f_{\max}[V_G]}{v_{th}\,\sigma_T N_C}\right) \tag{3}$$

where σ_T was capture cross section of the trap states, N_C is the density of states in the conduction band, v_{th} is the average thermal velocity of the carriers. $\sigma_T = 1.3 \times 10^{-14}\ \text{cm}^{-2}$, $N_C = 2.3 \times 10^{18}\ \text{cm}^{-3}$ and $v_{th} = 5.6 \times 10^{7}\ \text{cm s}^{-1}$ were assumed from Refs. [10,11]. This enables conversion from gate voltage to energy level $E_T - E_C$ as shown in Fig. 5 and shows a correlation between frequency dispersion and D_{it} towards the conduction band edge. Minimum D_{it} of untreated and 50 W Ar treated samples were determined to be $1.41 \times 10^{12}\ \text{cm}^{-2}\ \text{eV}^{-1}$ and $5.05 \times 10^{10}\ \text{cm}^{-2}\ \text{eV}^{-1}$ at -0.41 eV and -0.43 eV respectively.

Table 1 summarises key parameters from the MOS capacitor characteristics of this study. The sample pre-treated with the in-situ 50 W Ar prior to Al_2O_3 deposition demonstrates the best overall performance.

4. Conclusion

We have combined the TMA-first process, with an initial exposure to remote Ar plasma for Al_2O_3 deposition. As determined by frequency dispersion, hysteresis and D_{it} a 50 W in-situ Ar plasma pre-treatment for 5 min improves all key MOSCAP performance metrics. It is to be anticipated that this optimised in-situ Ar plasma process prior to Al_2O_3 deposition may result in improved GaN based MOS-HEMT performance for power electronics applications.

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