A study of the impact of in-situ argon plasma treatment before atomic layer deposition of Al₂O₃ on GaN based metal oxide semiconductor capacitor

S.J. Cho,⇑*, J.W. Roberts, I. Guiney, X. Li, G. Ternent, K. Floros, C.J. Humphreys, P.R. Chalker, I.G. Thayne

School of Engineering, University of Glasgow, Glasgow G12 8LT, UK

School of Engineering, University of Liverpool, Liverpool L69 3GJ, UK

Department of Materials Science & Metallurgy, University of Cambridge, Cambridge CB3 0FS, UK

Article history:
Received 20 February 2015
Received in revised form 27 March 2015
Accepted 10 April 2015
Available online 17 April 2015

Keywords:
Metal oxide semiconductor capacitor (MOSCAP)
Atomic layer deposition (ALD)
Argon pre-treatment
Gallium nitride (GaN)
Interface state density ($D_{it}$)

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 Al₂O₃ dielectric film is assessed by frequency dependent evaluation of Al₂O₃/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 $6.8 \times 10^{15}$ cm$^{-2}$ eV$^{-1}$ to $5.05 \times 10^{14}$ 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 Al₂O₃, HfO₂ and ZrO₂ 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 Al₂O₃ 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 Al₂O₃/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 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 N₂ 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 Al₂O₃ growth chamber, samples were cleaned using organic solvents. Before ALD deposition of Al₂O₃, 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 Al₂O₃ 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
deposition, windows were opened in the Al$_2$O$_3$ 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$_2$O$_3$/GaN interface.

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

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. 3 shows C–V characteristics of the Al₂O₃/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

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

where $C_{ox}$ is the oxide capacitance [9].

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

$$E_T - E_C = k_B T \ln \left( \frac{2\pi f_{max} |V_g|}{\nu_{th} \sigma_T N_C} \right)$$

where $\sigma_T$ was capture cross section of the trap states, $N_C$ is the density of states in the conduction band, $\nu_{th}$ is the average thermal

**Table 1**

<table>
<thead>
<tr>
<th></th>
<th>w/o PT</th>
<th>50 W Ar</th>
<th>150 W Ar</th>
<th>300 W Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{ox}$ (nm)</td>
<td>20.3</td>
<td>20.5</td>
<td>19.2</td>
<td>19.7</td>
</tr>
<tr>
<td>$C_{m} @ 5 \text{ V}, 1 \text{ MHz} (\mu\text{F/cm}^2)$</td>
<td>0.34</td>
<td>0.34</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>Hysteresis ($\Delta V$)</td>
<td>0.25</td>
<td>0.07</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>Frequency dispersion ($\Delta V$)</td>
<td>0.31</td>
<td>0.03</td>
<td>0.07</td>
<td>0.17</td>
</tr>
<tr>
<td>$D_{it} (10^{11} \text{ cm}^{-2} \text{ eV}^{-1})$</td>
<td>68.04</td>
<td>0.50</td>
<td>2.13</td>
<td>22.63</td>
</tr>
</tbody>
</table>

* Oxide thickness by ellipsometer.
* Measured total capacitance density.

Fig. 4. $G_p/\omega$ 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.

Fig. 5. $D_{it}$ as a function of trap energy level determined by the conductance method for various in-situ Ar pre-treatments.
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 $-0.41 \text{ eV}$ and $-0.43 \text{ eV}$ 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$_2$O$_3$ 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$_2$O$_3$ 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$_2$O$_3$ deposition may result in improved GaN based MOS-HEMT performance for power electronics applications.

#### Acknowledgements

The authors acknowledge financial support from the Engineering and Physics Sciences Research Council (EPSRC) under EP/K014471/1 (Silicon Compatible GaN Power Electronics).

#### References