Deposition and Characterization of ALD Dielectric Materials for Metal-Insulator-Semiconductor AlGaN/GaN High Electron Mobility Transistors

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Principal Investigator(s): Fatemeh Shahedipour-Sandvik

User(s): Benjamin McEwen

Affiliation(s): SUNY Polytechnic Institute, College of Nanoscale Science and Engineering

Primary Source(s) of Research Funding: Army Research Laboratory

Contact: sshahedipour-sandvik@sunypoly.edu, mcewen@sunypoly.edu

Primary CNF Tools Used: Oxford FlexAL ALD, Woollam spectroscopic ellipsometer

Abstract:

We continue our investigation of atomic layer deposition (ALD) for gate dielectric materials in AlGaN/GaN metal-insulator-semiconductor high electron mobility transistors (MISHEMTs). Al_2O_3, Si_3N_4, and SiO_2 were each tested. Pre- and post-deposition processes are found to greatly affect the quality of the dielectric and the dielectric/semiconductor interface. In particular, deposition of dielectric material as the first step in the fabrication process flow was found to be important. All devices fabricated with dielectric deposited after ohmic metallization exhibited high leakage currents and poor gate control. This presents a problem for Al_2O_3 MISHEMTs, since the Al_2O_3 has a relatively limited thermal budget and degrades at the temperatures necessary for ohmic metallization of GaN (~850°C).

Summary of Research:

The next generation of (Al)GaN power switches will likely require MIS gates in order to operate as normally-off devices with low leakage and high gate swing. Adding a gate dielectric however, complicates the process flow as additional considerations for stability of the dielectric during subsequent processing must be made, and the additional dielectric/semiconductor interface may contain a high density of interface trap states (D_{it}), leading to issues such as high dynamic on resistance (R_{ON}) and premature breakdown.

To determine the effect of forming a gas (95% N_2/5% H_2) anneal on the Al_2O_3/GaN interface, unintentionally doped (UID) GaN was grown on c-plane sapphire using metal-organic chemical vapor deposition (MOCVD) — 20 nm of Al_2O_3 was deposited using the Oxford FlexAL ALD system at CNF; the substrate was maintained at 300°C during the deposition.

Temp (°C)	1 min	10 min	20 min
600	X		X
475		X	
350	X	X	X

Table 1: Forming gas annealing conditions applied to Al_2O_3 after deposition.

After the deposition, samples were annealed in forming gas for a range of temperatures and times, as outlined in Table 1. MIS capacitors were subsequently fabricated, and the conductance method was used to extract the D_{it}. The D_{it} of the samples annealed at 350°C for 10-20 min was found to be over an order of magnitude less than that of the sample annealed at 600°C for 20 min and approximately half an order of magnitude less than the samples with as-deposited material, annealed at 350°C for 1 min, annealed at 475°C for 10 min, and annealed at 600°C for 1 min.

This indicates that annealing in forming gas for long times at lower temperatures is beneficial, while the material starts to degrade at higher temperatures. As ohmic metallization temperatures for GaN are ~ 850°C, this means Al_2O_3 must be deposited after the ohmic metallization [1].

To compare the necessary ohmic-first Al_2O_3 MISHEMTs with dielectric-first Si_3N_4 and SiO_2 MISHEMTs (these materials have high thermal budget), MISHEMTs were fabricated, using the Oxford FlexAL ALD system at CNF to deposit all dielectric materials; ~ 15 nm of each material was deposited, as measured using the Woollam spectroscopic ellipsometer at CNF.

As shown in Figure 1, in all cases, several orders of magnitude reduction in gate leakage current relative to a Schottky-gated HEMT was observed. However, the sample with Al_2O_3 gate dielectric (deposited after ohmic metallization) exhibited poor gate control, and instead showed a high I_{DS} regardless of the applied V_{GS} (Figure 2). It is believed that this is due to a highly defective and/or contaminated interface between the dielectric and semiconductor, imparting a high fixed positive surface charge, making it impossible to deplete the 2DEG channel before dielectric breakdown [2].

In order to potentially recover the GaN surface and improve the quality of the dielectric/semiconductor interface, surface cleaning treatments were performed on GaN; using X-ray photoelectron spectroscopy (XPS), it was found that a cleaning procedure consisting of consecutive NH_4OH, HCl, and HF resulted in the lowest surface coverage of carbon and oxygen on the GaN [2]. This cleaning procedure was applied to Al_2O_3/AlGaN/GaN MISHEMT devices prior to dielectric deposition.

After ohmic contact metallization, samples were cleaned with NH_4OH, HCl, and HF immediately before being loaded in the Oxford FlexAL ALD chamber at CNF; 8 nm of Al_2O_3 was deposited at 300°C. Completed devices exhibited more gate control than devices fabricated in the same run with only acetone/IPA clean prior to Al_2O_3 deposition, but high I_{OFF} ~ 190 mA/mm was measured at V_{DS} = 10 V, compared to I_{ON} ~ 340 mA/mm at V_{DS} = 10 V and V_{GS} = 0 V.

Even with surface treatments, the surface is not fully recovered, and additional measures must be taken to preserve the semiconductor surface if Al_2O_3 is to be a viable gate dielectric.

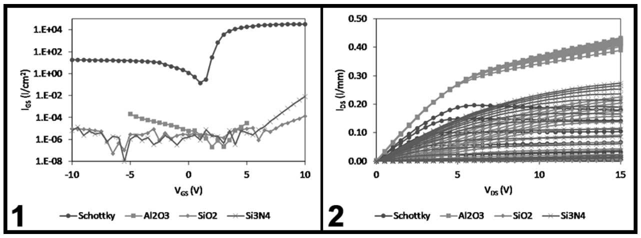

***Figure 1, left:** Gate leakage current for Al_2O_3, Si_3N_4, and SiO_2 MISHEMTs compared with conventional Schottky gate HEMT. V_{DS} = 5.5 V. **Figure 2, right:** Output characteristics for Al_2O_3, Si_3N_4, and SiO_2 MISHEMTs compared with conventional Schottky gate HEMT. The highest curves are at V_{GS} = 0 V, subsequent curves incremented V_{GS} down by 0.5 V. (See pages vi-vii for full color versions of both figures.)*

This is the subject of ongoing research.

References:

[1] B. McEwen, I. Mahaboob, E. Rocco, K. Hogan, R. Green, F. Nouketcha, T. Murray, V. Kaushik, A. Lelis, F. Shahedipour-Sandvik. "Investigation of the Effects of Forming Gas Annealing on Al_2O3/GaN Interface," submitted.

[2] B. McEwen, I. Mahaboob, K. Hogan, E. Rocco, V. Meyers, S. Tozier, A. Lelis, R. Green, F. Nouketcha, F. Shahedipour-Sandvik. "Effects of Semiconductor Surface Treatments and Dielectric Anneal on the Electrical Characteristics of GaN-Based Metal-Insulator-Semiconductor Devices." Poster presented at: 13th International Conf on Nitride Semiconductors; 2019 Jul 7-12; Bellevue, WA.