Electrical and Physical Characterization Investigation of Potential High-k Dielectrics on β-Ga_2O_3

C.D. Young[1], M.S.L. Narayanan[1], X. Qin[1], P. Zhao[1], A. Padovani[2], P. Bolshakov[1],
Jesus J. Alcantar Peña[1], L. Larcher[2], O. Auciello[1], and R.M. Wallace[1]

[1]University of Texas at Dallas, 800 W. Campbell Rd., Richardson, TX 75080, chadwin.young@utdallas.edu
[2]University of Modena and Reggio Emilia, Modena, Italy

Abstract – β-Ga_2O_3 has emerged as a candidate semiconductor for use in power/RF transistors which may incorporate a gate dielectric for MOS-HEMT devices. Thus, β-Ga_2O_3 capacitors with an Al_2O_3 dielectric were fabricated and characterized. XPS suggests that even though a Ga_2O state is detected, robust ALD growth of Al_2O_3 can be achieved on β-Ga_2O_3. Lack of frequency dispersion in multi-frequency C-V demonstrate the possibility of a relatively low interface state density. Furthermore, incorporation of thermally conductive microcrystalline diamond may help with β-Ga_2O_3 heat dissipation.

1. Introduction – The wide bandgap material (WBM), β-Ga_2O_3, has emerged as a candidate semiconductor for use in power/RF transistor applications which may exceed the performance of current semiconductors (e.g., SiC, GaN, and diamond.) due to the ability to operate at high frequencies, and high voltage [1-4]. Currently, High Electron Mobility Transistors (HEMTs) are the device structure of choice. However, HEMT structures can suffer from a significant parasitic leakage current at the Schottky junction that serves as the gate of the HEMT. Thus, combining WBM with a gate oxide could significantly reduce this effect and increase breakdown field strength, which has led to increased interest and investigation in many metal-oxide-semiconductor HEMT (MOS-HEMT) based technologies [5-7]. In addition, a particular challenge of β-Ga_2O_3 is its low thermal conductivity. Therefore, we have begun electrical and physical characterization to gain fundamental understanding of dielectric/β-Ga_2O_3 interfacial interactions.

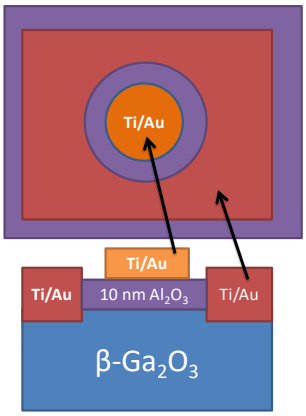
2. Experimental – Figure 1 illustrates the MOS capacitor schematic and process flow employed to fabricate β-Ga_2O_3 capacitors with an atomic layer deposited (ALD) Al_2O_3. The physical and electrical characterization was executed as outlined below.

3. Results and Discussion – The surface chemistry of a bulk, β-Ga_2O_3 was studied with X–ray photoelectron spectroscopy (XPS). First, XPS was conducted in a separate chamber attached to a cluster tool described elsewhere [8] prior to Al_2O_3 deposition in the ALD chamber. Then, after five cycles of ALD was done, XPS was performed again without breaking vacuum in an analysis chamber attached to the same cluster tool. The XPS results demonstrate that two chemical states, namely Ga_2O_3 and Ga_2O, are detected at the as-received β-Ga_2O_3 surface (Fig. 2a). The angle-resolved XPS Ga 3d indicates that the Ga_2O is likely closer to the outmost surface (Fig. 2b). After ALD of Al_2O_3, the surface chemical states detected do not change significantly, while the ALD Al_2O_3 is grown on the β-Ga_2O_3 successfully without any slow nucleation issues (Fig. 2c-e). A Keithley 4200 and Keysight E4980A executed current – voltage (I-V) and multi-frequency capacitance – voltage (C-V) measurements, respectively. With an Al_2O_3 thickness of 10 nm, low gate current values are expected and achieved (Fig. 3, inset). Multi-frequency C-V data, between 500 Hz and 1 MHz, was collected on several capacitors with representative data shown in Fig. 4. Results clearly demonstrate no significant frequency dispersion in the measured data, thereby suggesting no appreciable D_{it} at the β-Ga_2O_3/Al_2O_3 interface. Further investigation of trap response was preliminarily studied using pulsed C-V. In this measurement, the C-V sweep was executed in 500 μs rather than the tens of seconds required for conventional C-V measurements. Therefore, C-V data is collected in a fraction of the time required for normal C-V, and this enables the ability to measure C-V with significantly reduced time for trapping to occur during the measurement. Fig. 5 shows the pulse C-V response compared to the 100 kHz C-V where there is no significant difference between the two sets of data. This suggests there is no appreciable fast transient charge trapping [9] in this β-Ga_2O_3/Al_2O_3 system under the process conditions executed herein. As previously stated, one challenge for β-Ga_2O_3 device applications is the low thermal conductivity of β-Ga_2O_3. Single Crystalline Diamond (SCD) is known to be an excellent thermal conductor, as well as single crystalline diamond films, both of which exhibit thermal transport of about 2100 W/ K m in perpendicular and parallel planes to the surface. However, the problem with using single crystal diamond films grown on β-Ga_2O_3 – based devices to cool them is that single crystal diamond films can be grown only on fairly small and expensive single crystal diamond substrates. These are not suitable for lower-cost electronics like Si-based technologies. Polycrystalline diamond films would be an alternative to use as the cooling layers on β-Ga_2O_3 – based devices. We have significant experience in developing and working with a reliable industrial type process to grow extremely uniform microcrystalline diamond (MCD) to ultrananocrystalline diamond (UNCD) films on up to 300 mm diameter Si wafers [10, 11] where Auciello's group has shown that the thermal conductivity of the MCD film reach values of up to 1800 W/Km (Fig. 6a) [10] approaching that of single crystalline diamond. Therefore, we started to investigate a pathway to incorporate a low-cost industrial growth process for growing large area high thermal transport MCD films on β-Ga_2O_3 to produce efficient cooling of β-Ga_2O_3. One approach may involve growing a template layer of HfO_2 (≤ 30 nm thick) on the surface of β-Ga_2O_3, since Auciello's group already demonstrated the efficient growth of UNCD to MCD films on HfO_2 [11]. The polycrystalline diamond films grow very efficiently on the HfO_2 surface because the C atoms, from the CH_4 gas used to grow the diamond films via microwave plasma hemical vapor deposition (MPCVD) or hot filament chemical vapor deposition (HFCVD), react chemically with Hf atoms forming a nucleation HfC layer that induce the growth of the diamond films (Fig. 6b) [11].

4. Conclusion – Fabrication and characterization of β-Ga_2O_3 capacitors with Al_2O_3 was achieved. In-situ XPS study shows that ALD Al_2O_3 can grow on β-Ga_2O_3 without a nucleation issue or changing the initial surface. The Ga_2O state is detected at the initial starting surface, and the impact of Ga_2O will be further investigated. However, the initial electrical characteristics look quite promising for Al_2O_3 as a viable dielectric on β-Ga_2O_3 for MOS-HEMT applications. This is because there appears to be relatively low D_{it} signifying a potentially robust interface with β-Ga_2O_3. Furthermore, microcrystalline diamond could be a viable approach to enable the cooling of β-Ga_2O_3 with its challenges in thermal heat dissipation.

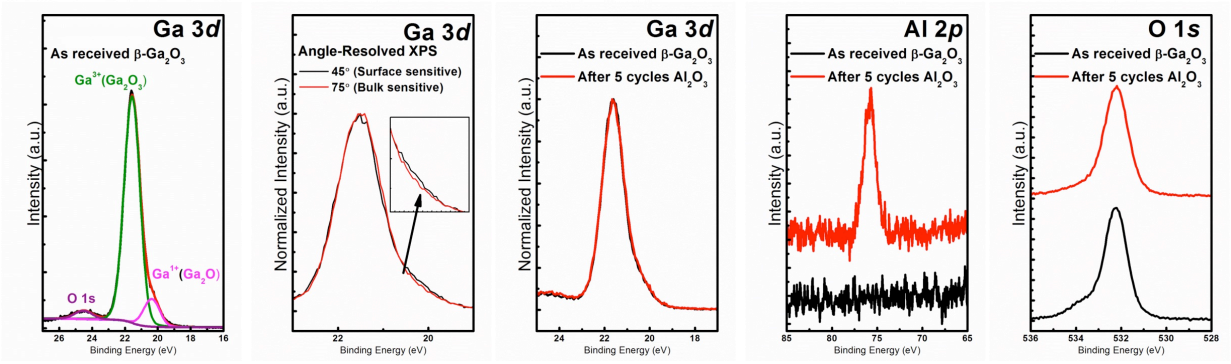
References

[1] S. Kohei, et al., *App. Phys. Exp.,* **5**, p. 035502, 2012.
[2] K. Irmscher, et al., *JAP,* **110**, p. 063720, 2011.
[3] W. S. Hwang, et al., *APL,* **104**, p. 203111, 2014.
[4] M. Higashiwaki, et al., *APL,* **100**, p. 013504, 2012.
[5] X. Qin, et al., *APL,* **107**, p. 081608, 2015.
[6] X. Qin, et al., *J. Mat. Sci.: Mat. in Elect.,* **26**, pp. 4638, 2015.
[7] X. Qin, et al., *APL,* **105**, p. 011602, 2014.
[8] R.M. Wallace, *ECS Trans.,* **16**, p. 255, 2008.
[9] C.D. Young, et al., *IEEE TED*, **56**, p. 1322, 2009.
[10] O. Auciello et al., *Diamond and Related Materials*, **19** , p. 699, 2010.
[11] J. J. Alcantar-Peña, et al., *Diamond and Related Materials*, **69** p. 221, 2016.



- ALD Al_2O_3 on Ga_2O_3
- PR pattern for the Ohmic metal
- Dry etching to open Ohmic window
- Ti/Au deposition for Ohmic contact
- Lift off
- PR pattern for the gate metal
- Ti/Au deposition for the gate metal
- Lift off

Fig. 1. Schematic and process flow for Al_2O_3/β-Ga_2O_3 capacitors.



(a) (b) (c) (d) (e)

Fig. 2. (a) XPS: Two chemical states (Ga_2O_3 and Ga_2O) are detected at the as received β-Ga_2O_3 surface. (b) The angle-resolved XPS Ga 3d indicates that Ga_2O is closer to the surface. (c) – (e) ALD Al_2O_3 did not change the surface chemical states significantly; however, ALD Al_2O_3 did grow successfully on the β-Ga_2O_3 without any slow nucleation issues.

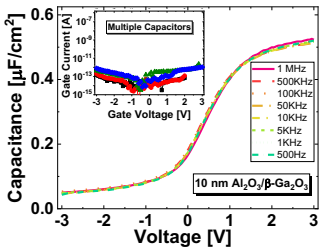


Fig. 3. Representative multi-frequency C-V data where negligible dispersion was observed, suggesting no appreciable D_{it}. Inset: low leakage I-V data from multiple capacitors.

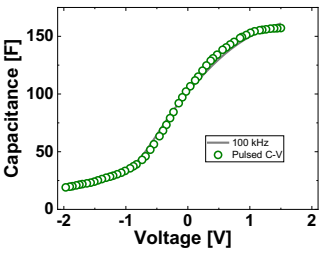


Fig. 4. Pulse C-V response compared to 100 kHz C-V data where there is no significant difference suggests there is no appreciable fast transient charge trapping in the Al_2O_3 dielectric.

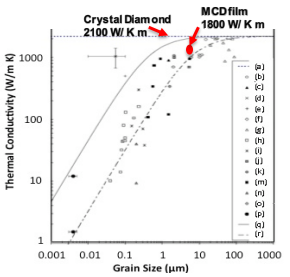


Fig. 5. MCD Thermal conductivity where the film can reach values of up to 1800 W/Km.

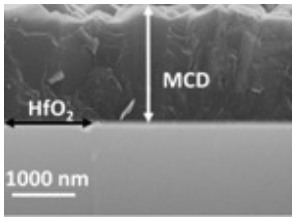


Fig. 6. Demonstration of a template layer of HfO_2 with a subsequent MCD deposited layer.