substrate with over 80 % of the wafer area covered with a uniform film. Films with growth rate of up to 1μm/hr have been demonstrated on a 2” sapphire substrates using both TEGa and TMGa precursors with an over all thickness uniformity of ~7 %.

The multi-wafer reactor was also used for the growth of Si doped and UID epitaxial β-Ga_2O_3 thin films on (010) β-Ga_2O_3 substrates. While the UID layer remains resistive, the doped sample has shown Hall mobility of ~ 90 cm^2/Vs at $n=1.6x10^{18}$ $1/cm^3$. The UID layer is expected to have high electron mobility but obtaining a good ohmic contact for accurate Hall measurement requires a complicated regrowth process [4]. These results clearly prove the capability of the CIS-MOCVD reactor for the growth of device quality β-Ga_2O_3 in high volume.

SILI CON DOPING IN A VMOCVD GROWN β-Ga_2O_3

In an MOCVD grown β-Ga_2O_3 layers, Si [8, 10] and Sn [8] are known as the most common doping impurities for achieving extrinsic n-type conductivity. Both impurities act as shallow donors. However, the use of Sn as a dopant for β-Ga_2O_3 grown by MOCVD is complicated for two reasons. The first is a pronounced memory effect. The second is the incoherency of Sn incorporation in β-Ga_2O_3 at high Sn doping levels (>10^{19} cm^{-3}) where it leads to a deterioration of the quality of the crystal and its surface. Moreover, the ionization efficiency of the Sn in the film is poor [8]. As a result, the use of Si appears to be the rational choice for n-type doping of MOCVD grown β-Ga_2O_3. In this study, we use a 40 ppm SiH_4/He as a source for Si to study its incorporation in an MOCVD grown Ga_2O_3 epitaxial films.

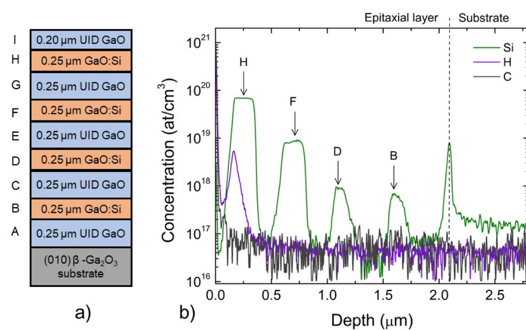

Fig.2. (a) Schematics of MOCVD grown β-Ga_2O_3multilayers doped with various concentrations of Si and O_2/TEGa ratios separated by UID layers. (b) SIMS depth profile of Si, H, and C for the multilayers in (a). The intentionally Si doped layers are marked with an arrow.

Here, multiple Si doped Ga_2O_3 layers with different concentration of Si are grown on a semi-insulating (010) β-Ga_2O_3 substrate in a single growth experiment. The growth rate for the layers is ~1μm/hr. The schematic representation of the Si doped layers is shown in Fig. 2 (a). The Si doped layers are separated by UID layers. Both for the doped and the UID layers, the O_2/TEGa ratio was varied to study its effect on the background concertation of Si, C, and H in the UID layers as well as the incorporation Si in the intentionally doped layers. The layers (A and B), (C and D), (E and F), and (G, H and I) are grown at O_2/TEGa ratios of 430, 1070, 2150, and 3220, respectively. The layers A, C, E, G and I are UID layers while the layers B, D, F, and H are intentionally Si doped layers with SiH_4/He flow rates of $2.3x10^{-10}$ mol/min, $2.3x10^{-10}$ mol/min, $2.3x10^{-9}$ mol/min, and $2.3x10^{-8}$ mol/min, respectively. The SIMS depth profiles for Si, C, and H in the layers are shown in Fig. 2 (b). At the film/substrate interface, the accumulation of Si is observed [10]. This accumulation of Si at the interface is similar to the phenomenon commonly encountered in MBE grown β-Ga_2O_3 which is frequently attributed to the adsorption of ambient contaminants onto the exposed substrate surface [11]. A similar contamination of the substrate surface might lead to the accumulation of Si at the film/substrate interface for the MOCVD grown β-Ga_2O_3 layers.

Figure 3 shows the Si concentration in the UID (blue trace) and intentionally Si doped (red trace) layers as a function of O_2/TEGa ratio and SiH_4/He flow rates. The increase of the O_2/TEGa ratio for the UID layers separating the intentionally doped layers yielded a similar background impurity concentration which is the detection limit of the SIMS instrument. However, for the intentionally doped layers the O_2/TEGa ratio appears to influence the incorporation of Si. The SiH_4/He flow rate in layers B and D is the same, but the concentration of Si atoms incorporated into the two layers is different. An increase in the O_2/TEGa ratio from 430 to 1073, led to the increase of Si atomic concentration from ~ $6x10^{17}$ to ~$9x10^{17}cm^{-3}$. This clearly indicates greater Si incorporation resulting from the increased oxygen flow. With the increase of the SiH_4/He and O_2/TEGa ratio, a Si concentration up to $7x10^{19}$ cm^{-3} was achieved. As indicated in the SIMS profile, a well-controlled Si doping of the Ga_2O_3 epilayer can be achieved by using SiH_4/He.

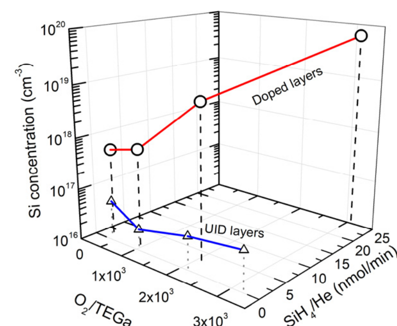

Fig.3. 3D graph showing the peak Si concentration as a function of O_2/TEGa ratio and SiH_4/He flow rate for the UID (blue) and Si doped (red) layers as measured by SIMS depth profile shown in Fig. 2(b).

The incorporation of carbon and hydrogen into the MOCVD grown Ga_2O_3 layers is anticipated due to the metalorganic precursors used for the growth of the films.

growth pressure and N_2O/TEGa ratio and separated by UID layers grown using pure oxygen. The *i*-GaO-I and *i*-GaO-II layers were grown at a chamber pressure of P_1 and N_2O/TEGa ratio of 4288 and 2144, respectively. Similarly, the *i*-GaO-III and *i*-GaO-IV layers were grown at a chamber pressure of P_2 ($P_1>P_2>100$ Torr) and N_2O/TEGa ratio of 4288 and 2144, respectively.

The SIMS depth profiles of N, H and C impurities in the layers grown with N_2O and oxygen are shown in Fig. 5 (b). The N_2O grown layers show an incorporation of N into the Ga_2O_3 films which drops to the detection limit (DL) in the UID Ga_2O_3 layers. The highest N incorporation ($\sim 1.9\times10^{19}$ cm^{-3}) is achieved for the *i*-GaO-II layer which is grown at a higher growth pressure (P_1) and lower N_2O/TEGa ratio of 2144. With the decrease in growth pressure, the incorporation of N into the N_2O grown layer is reduced. The UID layers between the N_2O grown layers don't contain any N, indicating that there is either very little or no diffusion of N out of the N_2O grown layers, which is consistent with the lower diffusion of N [16] observed in an implantation doped Ga_2O_3 substrate. However, the N doping is accompanied by the incorporation of H which virtually follows the same profile as N [see Fig. 5(b)]. This contrasts with the film grown using a pure oxygen precursor where there is no H incorporation observed. The use of N_2O may create a chemical byproduct that keeps the H in the growth chamber, but the exact cause of the H incorporation has yet to be understood. The incorporation of H along with N is undesirable as it effectively cancels the effect of N in the film given the shallow donor behavior of H. This requires the elimination, or at least the reduction, of H in the film while maintaining the N incorporation. This can be done either by annealing the film in vacuum or adjusting the growth conditions [18].

CONCLUSIONS

In summary, we demonstrated the viability of MOCVD to meet the demand for mass production of power devices based on Ga_2O_3. Multi-wafer CIS-MOCVD reactor that is capable of growing films on up to seven two-inch wafers in a single experimental run was used. Using TEGa and TMGa precursors, films with thickness uniformity < 10 % at a growth rate of ~1µm/hr have been demonstrated. UID and Si doped films have also been grown using the multi-wafer CIS-MOCVD. For the doped layer, RT Hall mobility of ~ 90 cm^2/Vs at $n=1.6\times10^{18}$ 1/cm^3 was measured. N-type conductivity and compensation doping of Ga_2O_3 using Si and Fe was studied. The incorporation of Si into the Ga_2O_3 thin film was dependent on the flow rates of SiH_4 and oxygen. For a constant SiH_4 flow, higher incorporation of Si was observed when the film is grown in an oxygen rich environment. Fe doping was conducted using ferrocene as a source for Fe. The increase in ferrocene flow rate leads to the incorporation of higher Fe into the film. However, Fe was observed to out diffuse into the UID layers, suggesting the need for the growth thick (~1.5 µm) UID layers to fully cap its effect from the active layers. N doping using N_2O for compensation was also studied. N, unlike Fe, was not observed to diffuse into the UID layers, making it an efficient compensating dopant. This is especially vital for film/substrate interface compensation where Si accumulation is common problem.

ACKNOWLEDGEMENTS

This work was supported by AFOSR and ONR programs through grant numbers FA9550-17-P-0029 and N00014-16-P-2058 under the directions of Dr. Ali Sayir and Mr. Lynn Petersen, respectively. The authors also acknowledge Prof. J. S. Speck and his research team for their support and collaborative contributions.

REFERENCES

[1] M. Higashiwaki et al., Phys. Status Solidi A **211**, 21(2014).
[2] F. Alema et al., APL Materials **7**, 022527 (2019).
[3] M. Higashiwaki et al. Appl. Phys. Lett. **100,** 013504 (2012).
[4] Y. Zhang et al., APL Materials **7**, 022506 (2019).
[5] K. Sasaki et al., J. Cryst. Growth **392**, 30 (2014).
[6] F. Alema et al., Phys. Status Solidi A **214**, 1600688 (2017).
[7] Y. Oshima et al. J. Cryst. Growth **410**, 53 (2015).
[8] M. Baldini et al. ECS J. Solid State Sci. Technol. **6**, Q3040 (2016).
[9] F. Alema et al., J. Cryst. Growth **475**, 77 (2017).
[10] R. Miller et al. IEEE Trans. Semicond. Manuf. **31**, 467 (2018).
[11] M. H. Wong et al. Jpn. J. Appl. Phys. **55**, 1202b9 (2016).
[12] J. L. Lyons et al. Phys. Rev. Appl. **2**, 064005 (2014).
[13] J. B. Varley et al., Appl. Phys. Lett. **97**, 142106 (2010).
[14] A. Kuramata et al. Jpn. J. Appl. Phys, **55**, 1202A2 (2016).
[15] F. Alema et al. "Device Quality β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$ Heterostructures—Control of Doping and Impurity incorporation in MOCVD Process," MRS Fall meeting, Boston, MA (2018).
[16] M. H. Wong et al., Appl. Phys. Lett. **113**, 102103 (2018).
[17] H. Peelaers et al. APL Materials **7**, 022519 (2019).
[18] A. Osinsky et al. "Low background impurity in an MOCVD grown β-Ga_2O_3" WOCSEMMAD, Jacksonville, FL Feburary 17-20, (2019).

ACRONYMS

CIS: Close Injection Showerhead
MOCVD: Metal Organic Chemical Vapor Deposition
MBE: Molecular Beam Epitaxy
HVPE: Halide Vapor Phase Epitaxy
MO: Metalorganic
TEGa/ TMGa: triethylgallium/trimethylgallium
UID: Unintentionally doped
SIMS: Secondary Ion Mass Spectrometry