Growth and Characterization of Gallium Oxide

Yacob Melman, Department of Chemical Engineering, Columbia University

2022 Platform for the Accelerated Realization, Analysis, and Discovery of Interface Materials Research Experience for Undergraduates Program at Cornell University (PARADIM REU @ Cornell)

PARADIM REU Mentor: Cameron Gorsak, Materials Science and Engineering, Cornell University

PARADIM REU Principal Investigator: Hari Nair, Materials Science and Engineering, Cornell University

Primary Source of PARADIM REU Funding: Support for PARADIM is provided under NSF Cooperative Agreement No. DMR-2039380 as part of the Materials Innovation Platform Program

Contact: ym2937@columbia.edu, cag284@cornell.edu, hn277@cornell.edu

Website: www.paradim.org/reu/cornell

Abstract:

Interest in gallium oxide has skyrocketed in recent years due to its potential use as a high breakdown field ultra-wide band gap semiconductor material. In addition to this, β-Ga_2O_3 is the thermodynamically stable phase which can withstand harsh environments and has several useful optical properties. Currently there is rapid commercial development of native melt-grown β-Ga_2O_3 substrates. Further research is needed to optimize epitaxial film growth of β-Ga_2O_3 for device applications. Metal organic chemical vapor deposition (MOCVD) is a promising solution due to its inherent scalability. MOCVD grown β-Ga_2O_3 films with a variety of different growth parameters were characterized by XRD, Hall effect measurements, optical reflectometry, and AFM in order to optimize the MOCVD growth process and demonstrate its viability for industry use.

Introduction:

Research in gallium oxide has gained prominence in recent years due to its potential use as a high breakdown field ultra-wide band gap semiconductor material. In addition to this, the thermodynamically stable β phase can withstand harsh environments due to its properties as an oxide and high melting temperature. β-Ga_2O_3 is optically transparent and possesses a bandgap of ~4.8 eV in the UV range. However, a scalable industry growth method has not yet been optimized. Metal organic chemical vapor deposition (MOCVD) is a possible solution, due to its inherent scalability. Careful characterization of films grown using this method, and consequent optimization of the growth process is necessary for industrial viability. Doping and alloying of the gallium oxide films was also experimented with in order to tune the carrier concentration and bandgap, respectively.

There are a number of different properties that are important to characterize. To detect and work to prevent grain boundaries and other defects, phase purity tests, such as 2θ-ω scans with an x-ray diffractometer, must be conducted. X-ray diffraction (XRD) ω scans allow for quantification of crystalline quality. Both optical reflectometry and x-ray reflectometry (XRR) are used to measure the thickness of films and reliably control the growth rate. A Hall measurement device can be used to obtain mobility and carrier concentration, both vital properties of semiconductors necessary for engineering device structures. The roughness of the films and their potential for use in devices must be analyzed through atomic force microscopy (AFM) in order to determine their feasibility for device fabrication.

Methods:

Films were grown using an Agnitron Agilis 100 MOCVD system on c-plane sapphire and 010 Fe-doped β-Ga_2O_3 substrates. During the growth process, various parameters were controlled and monitored, including molar gas flows, substrate temperature, and chamber pressure, in order to find an optimal setup. These films were analyzed using XRD. Various scans were performed to align to the substrate in order to optimize signal before performing 2θ-ω and ω scans. Optical reflectometry was performed on heteroepitaxial samples in order to order exploit the difference of refractive indexes between the film and substrate. AFM data was collected to determine surface roughness. XRD data was plotted and analyzed using MATLAB, while XRR, optical reflectometry, and AFM measurements were analyzed using OEM software.

Results and Discussion:

A 2θ-ω scan of gallium oxide grown on sapphire is shown below.

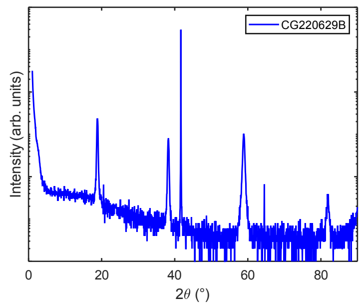

Figure 1: 2θ-ω scan of gallium oxide grown on a sapphire substrate, with degrees on the x-axis and intensity on the y-axis.

In the *2θ-ω* scan, three sharp peaks corresponding to the sapphire substrate and four broader peaks from the β-Ga_2O_3 film are seen. The film did not exhibit any additional peaks that would indicate alternative phases (most common being the defect structure γ-Ga_2O_3, which would appear at ~42).

An ω scan of homoepitaxial gallium oxide is shown below. Determination of the full width at half maximum (FWHM) of the peak found it to be ~47.6 arcseconds. This indicates fairly high quality, and is influenced heavily by the substrate quality.

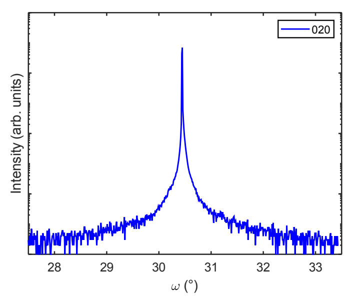

Figure 2: ω scan of a homoepitaxial β-Ga_2O_3 020 Bragg peak with a FWHM of ~47.6 arcseconds, with degrees on the x-axis and intensity on the y-axis.

Two *2θ-ω* scans of β-$(Al_xGa_{1-x})_2O_3$ grown on β-Ga_2O_3 are shown below, representing successful alloying experiments. In both, the substrate and film peaks are clearly visible, and Kiessig fringes are present which are indicative of high crystalline quality.

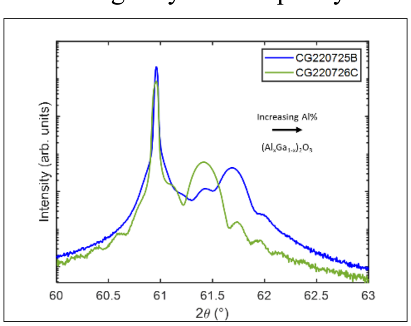

Figure 3: 2θ-ω scans of β-$(Al_xGa_{1-x})_2O_3$ *samples grown on* β-Ga_2O_3*, with Al concentrations of* $x \approx 10\%$ *and 17%, respectively, with degrees on the x-axis and intensity on the y-axis*

The temperature-dependent Hall mobility clearly shows the low impurity concentration, and the AFM indicates an RMS roughness of less than 2 nm, suitable for device application.

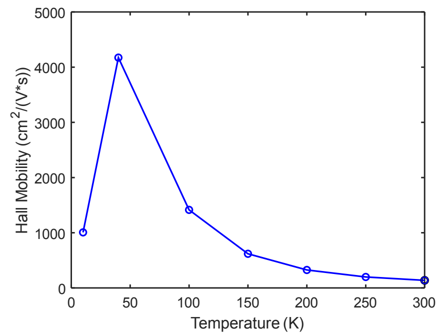

Figure 4: Temperature-dependent Hall mobility measurements for a lightly Si-doped homoepitaxial β-Ga_2O_3 *sample.*

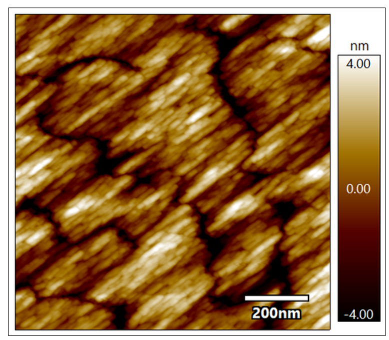

Figure 5: 5x5 µm AFM image of a homoepitaxial β-Ga_2O_3 *sample.*

Conclusions and Future Work:

Feedback from characterization techniques enabled continual optimization of the MOCVD growth system. High material quality for device application was demonstrated.

Further work will consist of *in situ* Si-doping of β-$(Al_xGa_{1-x})_2O_3$ films, as well as growth of heterostructures for device fabrication.

Acknowledgements:

I would like to thank my mentor, Cameron Gorsak, Dr. Hari Nair, and the Nair group as a whole for their help and guidance. My REU experience was supported by the National Science Foundation (Platform for the Accelerated Realization, Analysis, and Discovery of Interface Materials (PARADIM)) under Cooperative Agreement No. DMR-2039380. This research was supported by the Air Force Research Laboratory Cornell Center for Epitaxial Solutions (ACCESS) under Grant No. FA9550-18-1-0529.