Epitaxial Growth
Room Davis Hall 101 - Session EG+BG-TuA

Bulk/Epitaxy II

Moderator: Sriram Krishnamoorthy, University of California Santa Barbara

1:45pm **EG+BG-TuA-1 Suitable Orientation for Homoepitaxial Growth of Gallium Oxide*, Kohei Sasaki, A. Kuramata,*** Novel Crystal Technology, Inc., Japan **INVITED**

The surface orientation is an important condition in homoepitaxial growth. β-Ga_2O_3 has an unusual crystal structure, named β-Gallia, so we cannot use the knowledge of the usual crystal structures, such as diamond, zinc blende or wurtzite, when the selecting the surface orientation. Here, we investigated suitable orientations for homoepitaxial growth of gallium oxide by growing films on gallium oxide substrates with various orientations.

The β-Gallia structure is monoclinic, and its low index planes are (100), (010), and (001). We made gallium oxide substrate with surface orientations from the (100) to (010) plane or from the (100) to (001) plane and investigated the crystal quality, surface roughness, and growth rate of the films grown by molecular beam epitaxy. We sliced the surface in ten degrees steps from the (100) plane rather than adjusting the specific orientation. Growth temperature was fixed at 700 degrees Celsius. Ozone gas was used as the oxygen source.

Of the planes between the (100) and (010) plane, only the (100) plane showed a peculiarly low growth rate. On the other hand, there were no unusual features on the planes except the (100) plane; the growth rate was about 700 nm/h, and surface roughness (RMS) was about 1-2 nm.

On the other hand, the planes between the (100) and (001) plane showed severe surface roughness especially around the (101) plane and (-201) plane. The surface roughness on the (101) plane was due to crystal defects in which (-201) crystal grew on the (101) plane, whereas on the (-201) plane it was due to (-201) twin defects. We obtained very smooth surfaces with an RMS of 1 nm or less by using the (001), (-102), (401), (-401) planes.

It is known that the surface orientation of gallium oxide homoepitaxial growth depends on the growth method. The surfaces of films grown by MBE and metalorganic chemical vapor deposition (MOCVD) show similar morphologies. Thus, the knowledge gained in this research may be applicable to MOCVD.

2:15pm **EG+BG-TuA-3 Pushing the Al composition limit up to 99% in MOCVD β-$(Al_xGa_{1-x})_2O_3$ films using TMGa as Ga precursor*, A F M Anhar Uddin Bhuiyan,*** *L. Meng, H. Huang, J. Hwang, H. Zhao,* The Ohio State University

Recent research progresses have highlighted the promising potential of the MOCVD growth method in developing β-$(Al_xGa_{1-x})_2O_3$ alloys along different crystal orientations with high Al composition and controllable n-type doping. The coexistence of β and γ phases in (010) β-AlGaO films with Al>27% indicates challenges for incorporating higher Al compositions. Using alternative crystal planes of β-Ga_2O_3 substrates, such as (100) and (-201), has yielded single phase β-AlGaO films, with over 50% of Al incorporation. These prior efforts on MOCVD growth of β-AlGaO alloys using TEGa as the Ga precursor limit the film growth rate to below ~0.7 µm/hr.

In this study, we employed TMGa as the Ga precursor, which not only elevates the growth rates of β-AlGaO films up to 2 µm/hr, but also enhances the Al compositions up to a record high value of ~99%. The systematic investigation of MOCVD growth of β-AlGaO films and β-AlGaO/Ga_2O_3 superlattices on different crystal planes revealed a strong impact of substrate orientation on the solubility limit of β-AlGaO grown at relatively high growth rates. The crystalline structure, strain, morphology, stoichiometry, and bandgap of β-AlGaO films are investigated as a function of the Al composition and crystal orientations. β-AlGaO films with Al compositions up to 99%, 29%, 16% are achieved on (100), (010) and (-201) β-Ga_2O_3 substrates, respectively, as determined by XRD, XPS and STEM EDX. Beyond 29% of Al incorporation, the (010) β-AlGaO films exhibit β to γ phase transformation. Owing to its highly anisotropic characteristics, (-201) β-AlGaO films show local segregation of Al. Fully strained coherent β-AlGaO films are obtained for thicknesses of 350 nm (010, Al=15%), 120 nm (100, Al=16%) and 205 nm (-201, Al=13%). The crystalline structure of 20 nm thick β-$(Al_{0.99}Ga_{0.01})_2O_3$ film was accessed by atomic resolution STEM imaging, showing sharp interface and alloy homogeneity. The electron nano-diffraction pattern and quantitative STEM-EDX elemental mapping confirm the β-phase growth with Al composition of 99%, which agrees well with XRD and XPS measurement results. A record high bandgap energy of 7.26 eV is achieved from β-$(Al_{0.99}Ga_{0.01})_2O_3$ film using XPS, revealing great promises of developing β-AlGaO/Ga_2O_3 interfaces with high band offsets. The findings of this study offer valuable insights on the MOCVD epitaxy and properties of high Al composition β-AlGaO films and β-AlGaO/Ga_2O_3 heterostructures for device applications.

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2:30pm **EG+BG-TuA-4 Fast Growth and Characterization of Undoped β-Ga_2O_3 on 2-Inch Substrates Using a Horizontal Hot-Wall MOVPE System*, Kazutada Ikenaga,*** Tokyo University of Agriculture and Technology / TAIYO NIPPON SANSO CORPORATION, Japan*; J. Yoshinaga, P. Guanxi,* TAIYO NIPPON SANSO CORPORATION, Japan*; H. Tozato, T. Okuyama, K. Goto, Y. Kumagai,* Tokyo University of Agriculture and Technology, Japan

Metalorganic vapor phase epitaxy (MOVPE) is one of the attractive methods for the epitaxial growth of β-Ga_2O_3. However, it requires control of the hazardous reactions between organometallics and oxygen (O_2) while suppressing the incorporation of carbon (C) and hydrogen (H) impurities derived from the organometallics. Our research group has clarified the key conditions that enable the growth of high-purity β-Ga_2O_3 layers with suppressed C and H incorporation by thermodynamic analysis and in situ mass spectrometry of gaseous species in the reactor [1-3]. In this work, we report on the uniform and fast growth of β-Ga_2O_3 on 2-inch substrates.

A horizontal low-pressure hot-wall MOVPE system (TAIYO NIPPON SANSO CORPORATION, FR2000-OX) with a facedown holder capable of placing 2-inch diameter substrates was used. One 2-inch diameter c-plane sapphire wafer or three 10 mm × 15 mm sized β-Ga_2O_3(010) substrates were set for each growth. Epitaxial layers were grown in a temperature range of 900–1050 °C using trimethylgallium (TMGa) and O_2 as precursors, and Ar as a carrier gas, respectively. Under a constant O_2 supply, TMGa was supplied in the range of 111 – 546 µmol/min (corresponding to the input VI/III ratio from 1609 to 327).

The growth rate was found to be constant regardless of the growth temperature. At a growth temperature of 1000°C, the growth rate increased linearly up to about 15 µm/h with increasing TMGa supply rate, while the C impurity concentration increased. Since an increase in H and C impurity concentrations was observed with decreasing growth temperature, it is likely that the increase in these impurities is due to the increase in TMGa-derived hydrocarbons and their insufficient combustion. It was also found that there is no difference in growth rate between heteroepitaxial growth and homoepitaxial growth under the same conditions. In this presentation, the uniformity of the grown layer is also reported.

This work was supported by Ministry of Internal Affairs and Communications (MIC) research and development (JPMI00316).

[1] K. Goto et al., Jpn. J. Appl. Phys. **60**, 045505 (2021).

[2] K. Ikenaga et al., J. Cryst. Growth **582**, 126520 (2022).

[3] K. Ikenaga et al., Jpn. J. Appl. Phys., in press.

2:45pm **EG+BG-TuA-5 MBE Growth and Properties of Ultra-wide Bandgap Oxide Layers Spanning 5.0 - 9.0 eV Energy Gaps*, Debdeep Jena,*** Cornell University **INVITED**

3:15pm **EG+BG-TuA-7 Structural Defect Formation and Propagation in Fe-doped Czochralski-grown b-Ga_2O_3 Boules*, Luke Lyle,*** Pennsylvania State University - Applied Research Lab*; R. Lavelle,* Penn State University - Applied Research Lab*; D. Erdely,* Pennsylvania State University - Applied Research Lab*; W. Everson,* Penn State University - Applied Research Lab*; A. Balog, N. Alem,* Pennsylvania State University*; D. Snyder,* Pennsylvania State University - Applied Research Lab

Over the last decade, β-Ga_2O_3 has garnered increased attention due to its ultrawide bandgap of 4.7-4.9 eV, controllable range of shallow, n-type dopants (Sn, Si, Ge), and easily scalable and economic melt growth processes. Popular melt-growth processes that have been developed for β-Ga_2O_3 include the edge-defined film fed method, vertical bridgeman, and the Czochralski process. Although different types of structural defects in these melt-grown crystals have been identified, how they form and propagate throughout the growth process remains elusive. Specifically, it has been found that the density of structural defects can vary across wafers in the same boule and even across a single wafer.

We etch and analyze double side, chemi-mechanically polished 2” diameter wafers and 1” diameter wafers taken from ‘cores’ from 2” diameter boules at the tip, center, and tail of Fe-doped (010) Czochralski-grown boules. The etch pits were formed using an optimized H_2PO_4 etch process and are mapped using automated optical microscopy, statistical analysis software and scanning electron microscopy and are organized by defect type and density across each wafer analyzed in the boule. Wafers from the length of the boule were used to assess seeding and growth initiation related defect structures and long-range propagation and results from adjacent wafers at various locations were studied to understand short range defect formation and propagation. Trends regarding the presence of dislocations/nanopipes and their formation throughout the boule are discussed along with differentiation between process- and growth-related defects. Particular attention in this talk is paid to the formation and propagation of so-called “nanopipe” defects, as they are poised to act as killer-defects for high-voltage devices

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