Program Overview

Room /Time	Jefferson 2-3
TuA	EG-TuA: Bulk & Epitaxy II

Epitaxial Growth
Room Jefferson 2-3 - Session EG-TuA
Bulk & Epitaxy II

Moderator: Xiuling Li, University of Texas Austin

1:45pm **EG-TuA-1 Progress in Beta-Gallium Oxide Materials and Properties**, ***James Speck,*** University of California Santa Barbara **INVITED**

In this presentation, we present recent work on the development of β-Ga_2O_3 materials and their properties. The talk will include the following topics:

*Coherently strained β-$(Al_xGa_{1-x})_2O_3$ thin films on β-Ga_2O_3 Part I: Growth of (001) β-$(Al_xGa_{1-x})_2O_3$ thin films via metal oxide catalyzed epitaxy. In this work, we report on the growth of (001) β-$(Al_xGa_{1-x})_2O_3$ films in molecular beam epitaxy via metal oxide catalyzed epitaxy. Films with Al contents up to 15% were grown and Al content was measured with atom probe tomography. A relationship between Al content and out of plane lattice parameter was determined. Transmission electron microscopy showed no evidence of extended defects in the (001) β-$(Al_xGa_{1-x})_2O_3$ and reciprocal space maps confirmed that the β-$(Al_xGa_{1-x})_2O_3$ films were coherently strained to the (001) β-Ga_2O_3. Sn was also demonstrated to act as a surfactant for (001) β-$(Al_xGa_{1-x})_2O_3$ growth, allowing for high quality, uniform films with smooth morphologies.

*Coherently strained β-$(Al_xGa_{1-x})_2O_3$ thin films on β-Ga_2O_3 Part II - composition determination. We derive the relationships between lattice parameters for β-$(Al_xGa_{1-x})_2O_3$ and Al content x assuming the β-$(Al_xGa_{1-x})_2O_3$ is coherently strained to β-Ga_2O_3. The fundamental stiffness tensor of β-$Ga_2O_3$and stress-strain relationships are used to determine out of plane lattice parameters for (010) and (001) β-$(Al_xGa_{1-x})_2O_3$. Additionally, transformation of the stiffness tensor allows for derivation of similar relationships for (100) β-$(Al_xGa_{1-x})_2O_3$. For all three orientations, the relationships between peak spacing for β-$(Al_xGa_{1-x})_2O_3$ and β-Ga_2O_3 peaks in HRXRD and Al content x are calculated.

*We describe two recent ultrafast optical pump probe experiments that have determined the electron-phonon scattering time - 4.5 fs for electron-polar optical phonon scattering. These experiments also determined the energy separation of the CBM to the first side valley: 2.6 eV [Marcinkevicius et al., Appl. Phys. Lett. **118**, 242107 (2021)]. In a separate ultra-fast pump probe spectroscopy study, the time scale for the formation of polarons (from optically generated free holes) was determined: 0.5 to 1.1 ps [[Marcinkevicius et al., Appl. Phys. Lett. **116**, 132101 (2020)].

2:15pm **EG-TuA-3 (110) β-Ga_2O_3 Epitaxial Films Grown by Plasma-Assisted Molecular Beam Epitaxy**, ***Takeki Itoh,*** *A. Mauze, Y. Zhang, J. Speck,* University of California at Santa Barbara

Epitaxial growth of β-Ga_2O_3 with superior crystal quality has been achieved on different crystal orientations such as (100), (010) and (-201) via plasma-assisted molecular beam epitaxy (PAMBE)[1]. So far, most of the research has been performed on (010) substrates. However, investigation on (010) substrates has shown that (110) facets are revealed the chevron consistent features in RHEED studies, which indicates (110) is a natural plane in β-Ga_2O_3[2]. Figure 1 shows atomic models of (110) and (010) planes projected along [001] direction.

Unintentionally doped (UID) β-Ga_2O_3 epitaxial films were grown on (110) substrates by PAMBE while (010) substrates were co-loaded as growth reference. The temperatures of the substrates were kept at 600 ℃ and 700 ℃. To optimize the growth condition, the Ga fluxes were changed from 3.0×10^{-8} Torr to 2.5×10^{-7} Torr which were measured by beam equivalent pressure (BEP). Prior to the growth, oxygen polishing and Ga polishing were performed to remove the residual impurities from the surfaces. The film thickness was determined by measuring high-resolution X-ray diffraction (HRXRD). The surface morphology of the epitaxial films was measured by atomic force microscopy (AFM). Figure 2 shows the RHEED pattern of (110) and (010) substrates after Ga polishing. Streaky patterns were observed from the surface of (110) substrates, which indicates atomically flat surface. Conversely, crossed lines (red guideline) corresponding to (110) facets were observed from [001] azimuth on (010) substrate. Figure 3 shows the HRXRD result of the (110) β-Ga_2O_3 epitaxial film. Clear thickness fringes indicate abrupt interface between β-Ga_2O_3 and β-$(Al_{1-x}Ga_x)_2O_3$ spacer layers. Figure 4 shows the growth rate dependence on Ga flux of (010) and (110) substrates at 600 ℃ and 700 ℃. This result suggests that the growth rate is not reduced on the (110) plane compared to (010)[3]. In the oxygen rich regime, the growth rate increases linearly with Ga flux. In the plateau regime, there was still too low excess Ga flux to have a reduced growth rate. We expect higher Ga flux to yield reduced growth rates. Figure 5 shows the surface morphology of β-Ga_2O_3 films grown at 700 ℃ on (110) and (010) substrates. The RMS values indicate smooth surface morphology was obtained by growing on (110) substrates. Despite the appearance of (110) facets in the growth of (010) β-Ga_2O_3, the (110) plane does not have the tendency to show a well-defined step-terrace structure.

[1] A. Mauze *et al.,* APL Mater. **8**, 021104 (2020). [2] P. Mazzolini *et al.,* APL Mater. **7**, 022511 (2019). [3] T. Itoh *et al.,* Appl. Phys. Lett. **117**, 152105 (2020).

2:30pm **EG-TuA-4 Si-doped β-Ga2O3 Films Grown at 1 µm/hr by Suboxide MBE**, ***Kathy Azizie,*** *P. Vogt, F. Hensling, D. Schlom, J. McCandless, H. Xing, D. Jena,* Cornell University*; D. Dryden, A. Neal, S. Mou, T. Asel, A. Islam, A. Green, K. Chabak,* Air Force Research Laboratory

In this work we further develop suboxide molecular-beam epitaxy (S-MBE) to establish a means to Si-dope β-Ga2O3 grown by S-MBE and investigate its electrical properties. S-MBE was recently shown to enable the growth of β-Ga2O3 at growth rates exceeding 1 µm/hr with excellent crystallinity, surface smoothness, and at a low growth temperature. The key concept of S-MBE is to eliminate the first step of the two-step reaction mechanism involved in the growth of β-Ga2O3 by conventional MBE. In S-MBE, pre-oxidized gallium in the form of a molecular beam that is 99.98% Ga2O, i.e., gallium suboxide, is supplied. By eliminating the rate limiting step of conventional MBE—the oxidation of gallium to its suboxide—we achieve higher growth rates and avoid the etching that occurs in the conventional MBE growth of Ga2O3 at high fluxes of metallic gallium. Building upon S-MBE, we have studied Si-doped β-Ga2O3 films while maintaining a 1 µm/hr growth rate and high quality crystallinity, as confirmed by x-ray diffraction (XRD), atomic force microscopy (AFM), and reflection high-energy electron diffraction (RHEED). We investigate the incorporation and electrical properties of Si-doped β-Ga2O3 films using a variety of Si-based sources, including suboxide sources, with the goal of achieving replicable and controllable Si-doped β-Ga2O3 in the 1016 to 1018 cm-3 regime. The concentration of silicon incorporated as well as impurities present in the films are measured by secondary ion mass spectroscopy (SIMS). The electrical mobility and mobile carrier concentration is assessed by the Hall effect, including temperature-dependent Hall measurements. We have also fabricated and tested MESFETs from Si-doped β-Ga2O3 films grown by S-MBE at growth rates of 1 µm/hr.

2:45pm **EG-TuA-5 MOCVD Growth of Ga_2O_3 and $(Al_xGa_{1-x})_2O_3$**, ***Hongping Zhao,*** The Ohio State University **INVITED**

Ultrawide bandgap (UWBG) gallium oxide (Ga_2O_3) represents a promising semiconductor material with excellent chemical and thermal stability. Its wide energy bandgap (4.5-4.9 eV) predicts a breakdown field of 6-8 MV/cm, which is much larger than that of the 4H-SiC or GaN. The key advantages from this material system arise from the availability of high quality scalable bulk substrate and the capability of a wide range of doping.

Metalorganic chemical vapor deposition (MOCVD) growth technique has been demonstrated to produce high quality β-Ga_2O_3 thin films and its ternary $(Al_xGa_{1-x})_2O_3$ alloys. Record charge carrier mobilities approaching theoretical limit were reported from MOCVD grown materials. In this talk, I will discuss the control of background and n-type doping in MOCVD β-Ga_2O_3, and the impact of metalorganic precursor on Ga_2O_3 growth rate and material quality.

Growth and fundamental understanding of $(Al_xGa_{1-x})_2O_3$ with different phases are still limited. The limit of Al incorporation in beta-phase Ga_2O_3 has not been well understood or experimentally verified, although it was predicted up to 60% of Al composition could be incorporated into β-Ga_2O_3. In this talk, MOCVD growth of β-AlGaO with targeted Al composition of > 40%, n-type doping capability as a function of Al composition in $(Al_xGa_{1-x})_2O_3$, and MOCVD growth of different phase AlGaO will be discussed.

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Author Index

Bold page numbers indicate presenter