International Workshop on Gallium Oxide and Related Materials (IWGO-6)

Room ESJ 0202 - Session IWGO-TuM1

Substrate Development and Material Quality I

Moderators: Masataka Higashiwaki, Osaka Metropolitan University/NICT, **Yoshinao Kumagai**, Tokyo University of Agriculture and Technology

8:00am **IWGO-TuM1-1 Breakfast**

8:30am **IWGO-TuM1-7 Invited Paper*, Lynn Petersen,*** Office of Naval Research **INVITED**

8:55am **IWGO-TuM1-12 Cost Analysis of Gallium Oxide Wafer Production and Challenges and Strategies for Cost Reduction*, Akito Kuramata,*** *Takuya Igarashi, Shinya Watanabe,* Novel Crystal Technology, Inc., Japan*; Chia-Hung Lin,* Novel Crystal Technology, Inc., Taiwan*; Kohei Sasaki, Kimiyoshi Koshi,* Novel Crystal Technology, Inc., Japan **INVITED**

Gallium oxide has attracted significant attention as a promising material for next-generation power devices, and intensive research and development efforts on wafer and device technologies are being conducted worldwide toward its practical implementation. Applications are expected primarily in the medium- to high-voltage range, including wind power generation, photovoltaic systems, high-voltage direct current power transmission, energy storage systems, railway traction, fast charging for electric vehicles, and AI data centers.

In recent years, the rapid emergence of Chinese manufacturers has led to a substantial decline in the prices of SiC wafers and SiC power devices. For gallium oxide power devices to achieve commercial viability, they must outperform SiC not only in device performance but also in cost competitiveness. From this perspective, aggressive reduction of wafer manufacturing costs is of critical importance.

In this report, we analyze the cost structure of gallium oxide wafers and identify the key challenges that must be addressed to achieve future cost reductions. Furthermore, we discuss potential concrete strategies to overcome these challenges. Finally, we present the results of cost simulations estimating the extent to which wafer costs could be reduced after implementing the proposed measures.

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9:20am **IWGO-TuM1-17 Dawn of a 7 eV Semiconductor: Si-doped α–$(Al_xGa_{1-x})_2O_3$*, Darrell Schlom,*** Cornell University **INVITED**

For 65 years the highest bandgap semiconductor known has been cubic boron nitride (c–BN), with a bandgap (E_g) of 6.4 eV [1,2]. In the last few years this situation has changed, and a new semiconductor has emerged with higher E_g: α–$(Al_xGa_{1-x})_2O_3$. The first glimpse of this promising new semiconductor was conducting Si-doped α–$(Al_xGa_{1-x})_2O_3$ with E_g = 6.2 eV in 2020 [3]. This was followed by the prediction that silicon would be a shallow dopant in α–$(Al_xGa_{1-x})_2O_3$ for E_g up to 7.5 eV [4]. Then in 2024 Okumura's group showed conductivity up to E_g = 6.9 eV in Si-doped α–$(Al_xGa_{1-x})_2O_3$ [5,6]. Using a different growth technique—suboxide MBE (*S*–MBE) in which pre-oxidized molecular beams of the constituents, i.e., Ga_2O and SiO for the growth of Si-doped α–$(Al_xGa_{1-x})_2O_3$—and a sequence of buffer layers, we achieve conductivities more than 100 million times higher at $E_g \leq 7.0$ eV. In these structures we observe room-temperature mobilities as high as 90 $cm^2/(V\cdot s)$ for α-Ga_2O_3 [7]. Using a Si-doped α-$(Al_{0.51}Ga_{0.49})_2O_3$ channel layer with E_g = 6.7 eV, we fabricate Schottky diodes and MESFETs. Our results demonstrate the widest bandgap semiconductor in which active electronic device behavior utilizing controlled carrier transport and field-effect modulation has been achieved [8].

[1] R.H. Wentorf, "Preparation of Semiconducting Cubic Boron Nitride," *J. Chem. Phys.* **36** (1962) 1990–1991.

[2] R.M. Chrenko, "Ultraviolet and Infrared Spectra of Cubic Boron Nitride," *Solid State Commun.* **14** (1974) 511–515.

[3] G.T. Dang, Y. Tagashira, T. Yasuoka, L. Liu, and T. Kawaharamura, "Conductive Si-doped α-$(Al_xGa_{1-x})_2O_3$ Thin Films with the Bandgaps up to 6.22 eV," *AIP Adv.* **10** (2020) 115019.

[4] D. Wickramaratne, J.B. Varley, and J.L. Lyons, "Donor Doping of Corundum $(Al_xGa_{1-x})_2O_3$," *Appl. Phys. Lett.* **121** (2022) 042110.

[5] H. Okumura, A. Fassion, and C. Mannequin, "Si-doped $(AlGa)_2O_3$ Growth on *a*-, *m*- and *r*-Plane α-Al_2O_3 Substrates by Molecular Beam Epitaxy," *Jpn. J. Appl. Phys.* **63** (2024) 055502.

[6] H. Okumura, and J.B. Varley, "MOCVD Growth of Si-doped α-$(AlGa)_2O_3$ on m-Plane α-Al_2O_3 Substrates," *Jpn. J. Appl. Phys.* **63** (2024) 075502.

[7] J. Steele, J. Chen, T. Burrell, N.A. Pieczulewski, D. Bhattacharya, K. Smith, K. Gann, M.O. Thompson, H.G. Xing, D. Jena, D.A. Muller, M.D. Williams, M.K. Indika Senevirathna, and D.G. Schlom, "Growth of Conductive Si-Doped α-Ga_2O_3 by Suboxide Molecular-Beam Epitaxy," *APL Mater.* **13** (2025) 101117.

[8] This work was performed in collaboration with J. Steele, D. Bhattacharya, K. Nomoto, N.A. Pieczulewski, P. Sorenson, M. Ramesh, I. Shukla, S. Das, V-A. Ha, F. Giustino, B. Mazumder, M.K. Indika Senevirathna, M. Schubert, D.A. Muller, H.G. Xing, and D. Jena.

9:45am **IWGO-TuM1-22 Demonstration of 150 mm (001) β-Ga2O3 Substrates Grown by EFG Method*, Sho Hasegawa,*** *Kimiyoshi Koshi, Yuki Ueda, Ryoichi Sakaguchi,* Novel Crystal Technology, Inc., Japan*; Isao Sakamoto,* Novel Crystal Technology, Inc, Japan*; Keita Konishi, Makoto Mizui, Yu Yamaoka, Shinya Watanabe, Kohei Sasaki, Akito Kuramata,* Novel Crystal Technology, Inc., Japan

While 100-mm (001) β-Ga_2O_3 substrates are commercially available and have been successfully utilized in high-voltage, high-current devices, scaling the substrate diameter from 100 mm to 150 mm is essential for full-scale mass production. In this study, we report the growth of 150-mm (001) β-Ga_2O_3 single crystals using the edge-defined film-fed growth (EFG) method, along with the successful fabrication of 150-mm (001) substrates.

10:00am **IWGO-TuM1-25 Bulk Single Crystal Growth ofβ-Ga_2O_3 with Automatic Diameter Control System Specialized for the OCCC Method*, Masanori Kitahara,*** *Taketoshi Tomida,* FOX Corporation, Japan*; Vladimir Kochurikhin, Gushchina Liudmila,* C&A Corp, Russian Federation*; Yasuhiro Shoji, Kei Kamada,* FOX Corporation, Japan*; Koichi Kakimoto,* Tohoku University, Japan*; Akira Yoshikawa,* FOX Corporation, Japan

The Oxide Crystal Growth using a Cold Crucible (OCCC) method is scalable, crucible-free growth technique. We have previously reported the growth of oxide single crystals, including 2–inch–diameter β–Ga_2O_3, by taking advantage of the OCCC method [1,2], With simulation–assisted optimization of growth parameters such as oscillator frequency [3], single crystal growth was successfully demonstrated. However, manual diameter control based on visual observation has made it difficult to achieve smooth seeding and shoulder formation, posing a major challenge for long–length bulk crystal growth. In this study, a dedicated automatic diameter–control (ADC) system was developed, and its application to β–Ga_2O_3 bulk single–crystal growth is reported

Experimental: *β*-Ga_2O_3 crystal growth was conducted using an OCCC system equipped with a water-cooled copper basket with a 150 mmdiameter and an induction heating system with a 60 kW oscillator capacity. High-purity (99.999%) *β*-Ga_2O_3 powder was used as the starting material, and growth was performed in an air atmosphere. A*β*-Ga_2O_3(100)seed crystal was rotated at 2-5 rpm with a pulling rate of 1–4 mm/h.

Result:ADC system specialized for the OCCC method has been developed for the first time in the world. Smooth ADC step growth following the prescribed diameter was achieved from seeding through the shoulder, body, and tail parts, resulting in the successful growth of a bulk single crystal with a 30 mm diameter and 50 mm–long body. The dedicated ADC makes it possible to achieve crystal mass production in a way analogous to the conventional Cz method.Initial assessments using X-ray rocking curve (XRC) mapping of representative wafers confirm high crystallinity with narrow FWHM values across the surface, indicating minimal mosaicicity.The crystallinity, including dislocation density and electrical properties of the grown crystals will be discussed in detail during the presentation.

[1] A. Yoshikawa et al., Scientific Reports, 14. 1: 14881 (2024).

[2] K. Kamada et al., Crystals 2023, 13, 921.

[3] K. Kakimoto et al., J. Cryst. Growth, vol. 622, p. 127029 (2023).

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10:15am **IWGO-TuM1-28 Development of High-Quality 4" β-Ga_2O_3 (010) Wafer via the VB Method*, Yuki Yamamoto,*** *Shigenori Shimizu,* OXIDE, Japan*; Kensuke Mizukoshi, Takashi Nishinoiri,* Ceratec Japan Co., Ltd., Japan*; Toshinori Taishi, Keigo Hoshikawa,* Shinshu Univ., Japan

Most commercially available β-Ga_2O_3 wafers are grown by the edge-defined film-fed growth (EFG) method; however, circular wafers are limited to the (001) or (201) orientations. In contrast, the vertical Bridgman (VB) method enables the growth of circular wafers with (100), (010), and (001) orientations, and the growth of 4-inch-diameter single crystals has been reported. In this study, Fe-doped [010] β-Ga_2O_3 single crystals with a diameter of 4 inches were grown by the VB method. The obtained crystals were sliced and polished to fabricate (010)-oriented wafers. X-ray topography and X-ray rocking curve measurements were carried out for evaluation. The grown crystal exhibited a constant-diameter region of 30 mm without twins or cracks. A 500 um thick wafer was obtained by slicing and polishing. Although wafer warpage was observed after single-side polishing. The warpage was reduced after double-side polishing. The full width at half maximum obtained from X-ray rocking curve measurements was approximately 15 arcsec. Reflection X-ray topography showed diffraction contrast over the entire wafer area, indicating that the wafer is free from not only twins and cracks but also low angle grain-boundaries.

Author Index

Bold page numbers indicate presenter