International Workshop on Gallium Oxide and Related Materials (IWGO-6)
Room ESJ 0202 - Session IWGO-WeM1

Plenary Session II

Moderators: Martin Albrecht, Leibniz Institute for Crystal Growth, **Huili (Grace) Xing**, Cornell University

8:00am **IWGO-WeM1-1 Breakfast**

8:45am **IWGO-WeM1-10 PLENARY: From Crystal Growth to Power Devices: The Evolution of Gallium Oxide Technology*, Kohei Sasaki,*** Novel Crystal Technology, Inc., Japan **INVITED**

Gallium oxide has attracted significant attention as an ultra-wide-bandgap semiconductor with the potential to enable power devices with lower losses than conventional Si, SiC, and GaN technologies [1]. Over the past 17 years, I have been engaged in research on gallium oxide power devices.

In the early 2000s, this research field was still in its infancy, attracting only a limited number of researchers from different parts of the globe. Device prototypes were fabricated on small crystal pieces of only a few millimeters in size, and demonstrations were limited to extremely small-area devices carrying currents on the order of milliamperes. Since then, remarkable progress has been achieved. Today, 6-inch gallium oxide substrates are becoming available [2], and device technologies have advanced to the point where 100-A-class devices can be demonstrated. In parallel, the research community has expanded significantly and is now estimated to exceed 1,000 researchers worldwide.

In terms of epitaxial growth, molecular beam epitaxy was initially the dominant technique; however, alternative methods such as halide vapor phase epitaxy (HVPE) and metal-organic chemical vapor deposition have been developed to enable thick epitaxial layers suitable for vertical power devices. Using HVPE-grown epitaxial wafers, recent demonstrations have included 1.8-kV trench MOS-type Schottky barrier diodes and 10-kV-class FinFETs with performances comparable to state-of-the-art SiC devices. Further improvements, such as electric field management using heterojunctions with p-type NiO, are expected to unlock performance levels beyond the reach of SiC devices in the near future.

Another long-standing challenge has been the high substrate cost associated with the use of expensive noble-metal crucibles. Recently, several metal crucible-free bulk growth techniques have been reported, suggesting promising pathways toward cost reduction [3, 4].

In this keynote, I will reflect on the 17-year evolution of gallium oxide research, from its early stages to the present, and offer my perspective on its future directions.

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9:30am **IWGO-WeM1-19 Homoepitaxial Growth of β-Ga_2O_3 Using HVPE and MOVPE*, Yoshinao Kumagai,*** Tokyo University of Agriculture and Technology, Japan **INVITED**

β-Ga_2O_3 has attracted considerable attention as a power device material owing to its high breakdown field of ~8 MV/cm [1]. Furthermore, the availability of large-area single-crystal substrates grown by various melt-growth methods [2–6] has promoted extensive research on the fabrication of substrates with homoepitaxial layers having controlled conductivity. Our research group has conducted extensive studies on two homoepitaxial growth techniques capable of medium-to-high growth rates, namely halide vapor phase epitaxy (HVPE) [7–11] and metalorganic vapor phase epitaxy (MOVPE) [12–14], which are applicable to the growth of homoepitaxial layers for both lateral and vertical device structures.

In HVPE, GaCl and O_2 served as sources, enabling homoepitaxial growth on (001) substrates at atmospheric pressure with growth rates of 0.4–19 µm/h, yielding high-purity layers [7,8]. Si and N concentrations were controlled in the ranges of 1×10^{16}–3×10^{18} and 3×10^{18}–1×10^{21} cm^{-3} by intentional $SiCl_4$ [9] and NH_3 [11] doping, respectively, although the growth rate strongly depended on the substrate orientation [10]. In MOVPE, trimethylgallium and O_2 were used as sources, enabling homoepitaxial growth of high-purity layers at 0.9–16 µm/h under reduced pressure and high O/Ga supply ratios [12,14], comparable to HVPE. Si concentrations were controlled in the range of 2×10^{15}–2×10^{19} cm^{-3} by intentional tetramethylsilane doping [13]. In this talk, the growth mechanisms of β-Ga_2O_3 in HVPE and MOVPE, as well as the progress in homoepitaxial growth, the current status including device applications, and challenges, will be presented.

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9:55am **IWGO-WeM1-24 Characterization of Shallow and Deep Level Defects in β-(AlxGa1-x)2O3 Bulk Crystals*, Andreas Fiedler,*** Leibniz-Institut für Kristallzüchtung, Germany **INVITED**

β-Ga_2O_3alloyed with aluminum has a larger bandgap which can be used in heteroepitaxy to generate an interface 2-dimensional electron gas (2DEG) due to the suitable band alignment. Such structures can potentially be used in high electron mobility transistors (HEMT). For a better understanding of the material a detailed defect investigation on Czochralski grown bulk crystals was carried out. Details on crystals growth, crystal structural quality, and properties can be found elsewhere [1, 2].

In this work, we investigated unintentionally doped single crystals with varying aluminum concentration and report on a shift of activation energies for multiple deep defect states. The electron mobility values are significantly decreasing with increasing Al content, most likely due to an increase in the scattering of optical phonons caused by the lattice mismatch and an increased alloy scattering [1]. The activation energies of the majority carriers are in the range of 20 meV to 30 meV but showing no strong influence by the Al-content.

To gather information about deep level states, Deep-Level Transient Spectroscopy (DLTS) was performed in the temperature range from 20K to 800K. We found three major peaks of deep level states with a significant shift to higher ionization energies regarding to the conduction band edge with increasing Al incorporation. The most prominent peak, which is consistent with the previously reported iron based deep acceptor state (E2) [3], shifts from around 0.7 eV to 1eV with increasing [Al] from 0% to 20%.

Concluding, the electrical properties of β-Ga_2O_3 and the aluminum alloyed β-$(Al_xGa_{1-x})_2O_3$ are comparable. While we do not observe a shift of activation energy for the primary shallow donor silicon, we can observe a clear shift of the ionization energies of deep states to higher energies with increasing aluminum content in the alloy. However, this shift of the ionization energy is comparably low to the shift of the overall band gap. This study can give insights in the applicability of the scissor function in DFT calculations of defect states in the β-$(Al_xGa_{1-x})_2O_3$ alloy.

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