

Epitaxy of β -Ga₂O₃ on Highly-Offcut ($>10^\circ$) Substrates

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β -Ga₂O₃ has emerged as a leading candidate for next-generation power electronics, radio frequency (RF) switches, and extreme environment electronics due to a wide band gap (4.6 – 4.9 eV), high dopability (~ 40 meV activation energy for an isolated silicon donor), and melt growth characteristics resulting in commercially available 4-inch substrates and commercial demonstrations of 6-inch substrates by multiple techniques.

The (100) surface of Ga₂O₃ is highly desirable from a device and epitaxy standpoint – bulk growth of (100) material is more scalable than (010), the surface is nearly lattice-matched to p-type partner NiO, and Al₂O₃ incorporates at higher concentrations without phase separation. However, the epitaxial growth rate on (100) surfaces is less than 10% of other faces due to weak bonding and favorable desorption. Recent demonstrations have shown growth rate improvements from 0.4 nm/min to 1.5 nm/min by growing on (100) wafers that are offcut 6° in the $-c$ direction.¹ These films show step-flow growth from (-201) step-edges and high electron mobility. Despite these exciting results, offcuts greater than 6° have not been explored due to the waste associated with grinding and polishing large offcuts.

In this talk we will discuss the molecular beam epitaxy (MBE) growth and properties of β -Ga₂O₃ grown on (100) substrates offcut in the $-c$ direction up to 13.4° . These large offcuts are enabled by edge-fed film-defined growth (EFG) where the offcut is grown into the surface by pulling the crystal through the EFG die with the seed crystal rotated by the desired offcut angle. We will demonstrate that 13.4° offcut substrates still exhibit a terraced (100) surface, and that a $>10\times$ increase (4.8 nm/min) in growth rate is achieved. As previously reported on lower offcuts, we observe 100% reversal of substrate twin domains around the (001) direction at the substrate-epilayer interface. We will discuss electrical properties including record-low (by MBE) unintentional doping densities of $< 5 \times 10^{15} \text{ cm}^{-3}$.

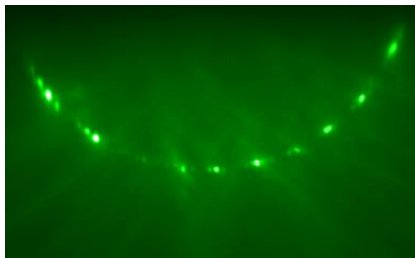


Figure 1. RHEED of 13.4° offcut Ga₂O₃ substrate.

[1] R. Schewski, APL Mater. 7, 022515 (2019).

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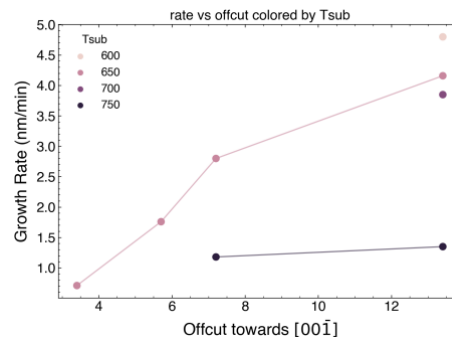


Figure 2. Rate versus offcut and temperature.

Supplementary Pages

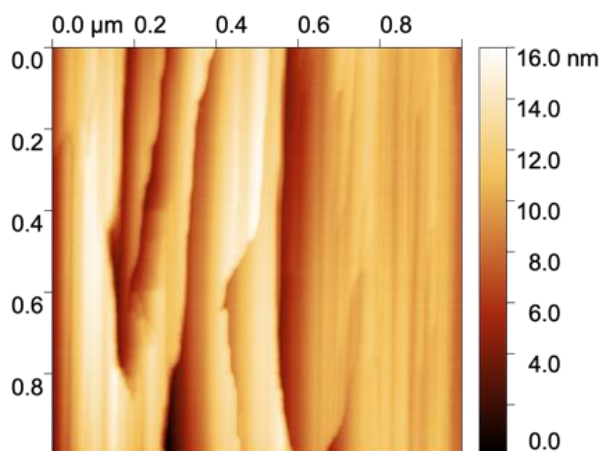


Figure S1. Atomic force microscopy of an MBE-grown epilayer on a 13.4° offcut Ga_2O_3 substrate showing highly inclined terraces and step bunching.

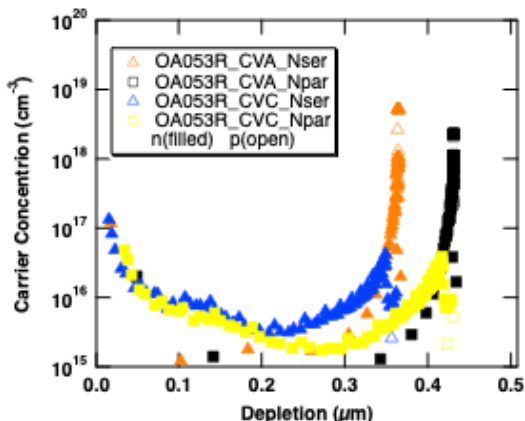


Figure S2. Electrochemical C-V of MBE-grown epilayers with $<5\text{E}15 \text{ cm}^{-3}$ unintentional doping density

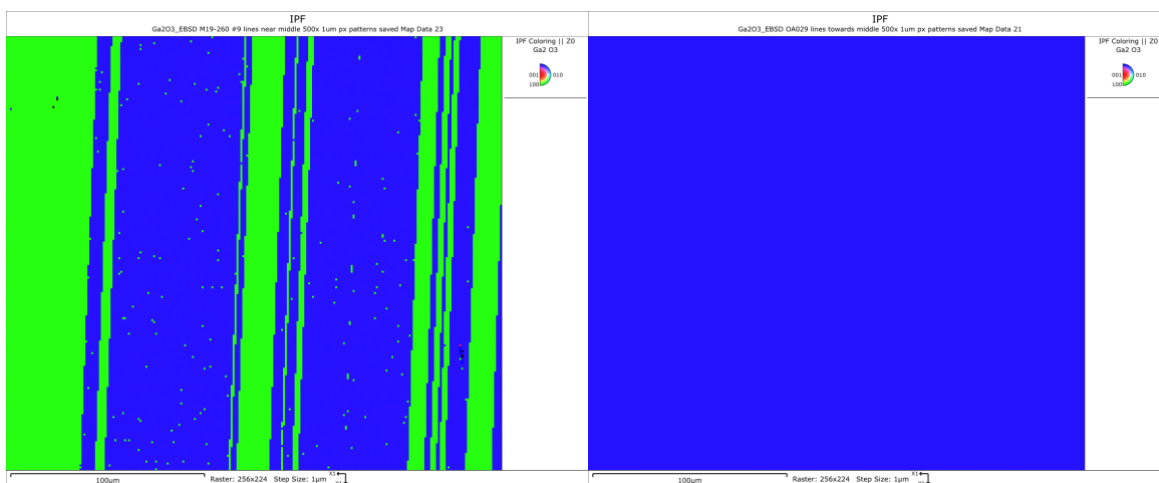


Figure S3. Electron Backscatter Diffraction (EBSD) inverse pole figures of a 13.4° $\beta\text{-Ga}_2\text{O}_3$ substrate (left) showing twin domains flipped along the (001) axis. Epilayers grown on these substrates (right) show 100% reversal of twin domains.

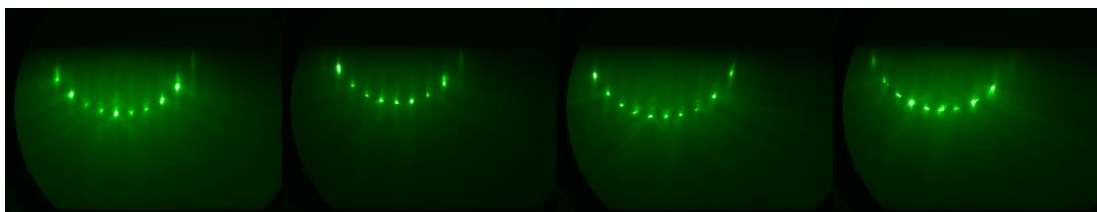


Figure S4. Reflection high-energy electron diffraction (RHEED) images of as-loaded substrates with offcuts of 3.4°, 5.7°, 7.2°, and 13.4° from left to right show a (100) terraced surface with increasing inclination.