Stability of Interface Morphology and Thermal Boundary Conductance of Direct Wafer Bonded GaN|Si Heterojunction Interfaces Annealed at Growth and Annealing Temperatures

K. Huynh,[1] M. E. Liao,[1] X. Yan,[2] J. Tomko,[3] T. Pfeifer,[3] V. Dragoi,[4] N. Razek,[4,5] E. Guiot,[6] R. Caulmilone,[6] X. Pan,[2] P. E. Hopkins,[3] M. S. Goorsky[1]

[1] *University of California Los Angeles, Los Angeles, CA, 90095, USA*
[2] *University of California Irvine, Irvine, CA, 92697, USA*
[3] *University of Virginia, Charlottesville, Virginia, 22904, USA*
[4] *EV Group, 4782, Sankt Florian am Inn, Austria*
[5] *G-Ray Medical, Rouges-Terres 61, 2068 Hauterives NE, Switzerland*
[6] *Soitec, 38190, Bernin, France*

Evolution of the structural and thermal interfacial properties of direct wafer bonded (0001) GaN to (001) Si during annealing is investigated. Direct wafer bonding provides a pathway to fabricate and engineer heterointerfaces free of lattice mismatch restrictions. Here, an EVG® ComBond® wafer bonder was used to bond the GaN and Si under high vacuum at room temperature by first removing native oxide with an Ar^+ beam prior to bonding. We have demonstrated as-bonded GaN on Si with high thermal boundary conductance of 143 MW/(m^2·K) prior to annealing. High resolution transmission electron microscopy of the as-bonded structure revealed abrupt bonded interfaces with a ~1.3 nm amorphous interface due to the Ar^+ surface treatment. After annealing at 450 °C up to 7 hours, a 1 nm Ga-rich layer is observed across the interface near the surface of the Si in addition to SiN_x formation at the original bonded interface. Further annealing at 700 °C up to 24 hours led to the formation of Ga-rich pyramidal features that form across the bonded interface in the Si along the (111) planes. While recrystallization was observed to have a beneficial impact in other bonded systems, the chemical and structural reconfiguration of these GaN-Si interfaces resulted in poorer interfacial thermal transport by a factor of two (71 MW/(m^2·K)). This reduction is attributed to the degradation of thermodynamically less stable phases as the GaN breaks down into SiNx and Ga in the presence of silicon. We show that high TBC can be achieved through wafer bonding of GaN and Si and that interfacial properties that are stable at typical device operating temperatures (250 °C), but higher temperature annealing processing steps are deleterious to thermal transport across GaN-Si interfaces.

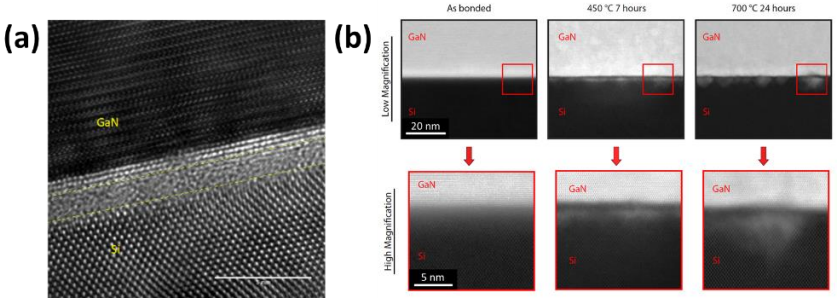

Figure 1. (a) TEM cross-section of the as-bonded GaN|Si interface. (b) STEM images of the bonded interface: as-bonded, after 450 °C for 7 hours, and 700 °C for 24 hours. Ga-rich pyramidal features formed along the (111) Si planes after 700 °C, which appears as bright contrast in the Si region.

+ Author for correspondence: goorsky@seas.ucla.edu

Supplementary Information

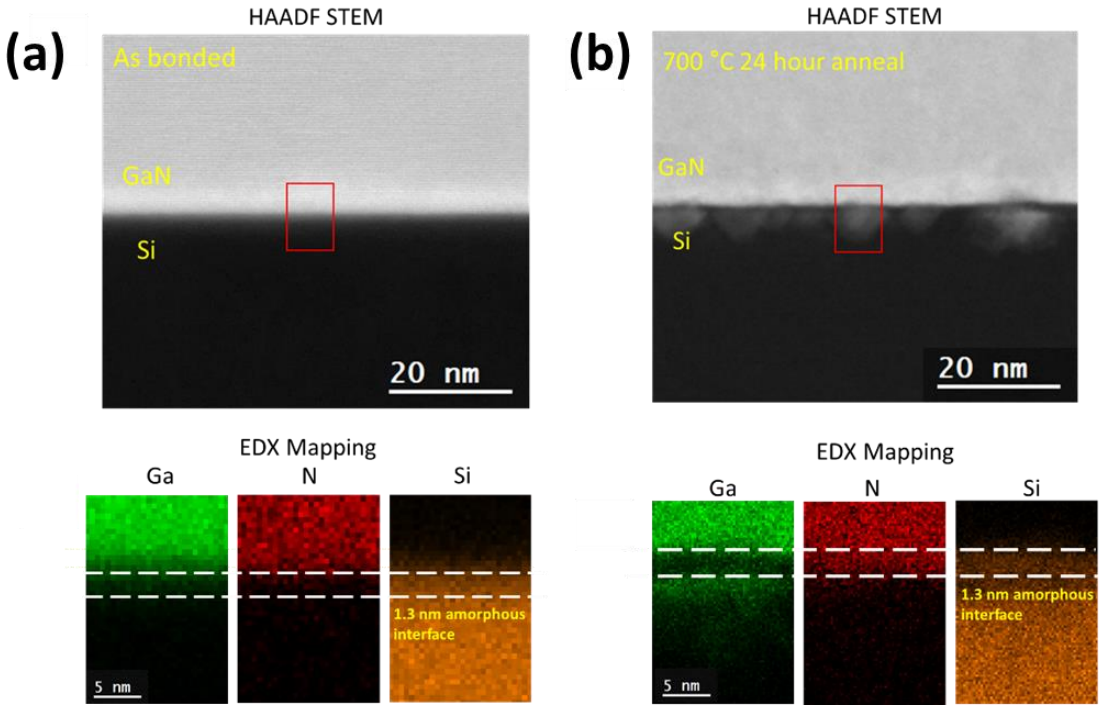

Figure S1. (a) Energy dispersive spectroscopy shows a chemically sharp interface in the as bonded sample. Additionally, comparison with electron microscopy reveals that the amorphous interface lies on the silicon side. (b) Energy dispersive spectroscopy and transmission electron microscopy reveals an amorphous interface that contains silicon and nitrogen and pyramidal shaped features where the gallium diffused across the interface.

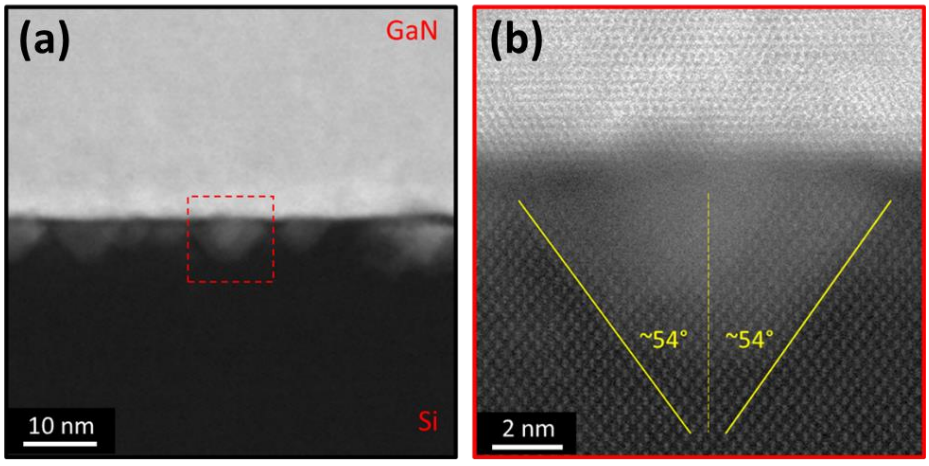

Figure S2. a) HAADF STEM images of Sample_700.24, which show brightly contrasted Ga-rich pyramidal regions ~3-6 nm deep into the Si. (b) HRSTEM images of one pyramidal Ga-rich region that shows these features follow the (111) Si planes (outlined in yellow).