**From Crystal Symmetry to Heat Flow: Resolving Anisotropic Transport in Gallium Oxide Phases**

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In low-symmetry monoclinic crystals with non-orthogonal axes the anisotropic nature of properties such as elasticity and dielectric response gives rise to unconventional phenomena, including hyperbolic sheer polaritons1, charge density waves or topological phase transitions not observed in higher symmetry materials2. In this work, we present a comprehensive, contactless investigation into the anisotropic phonon-governed properties of the ultra-wide bandgap semiconductor Ga₂O₃, with a focus on both nanoscale phonon dynamics and nanoscale thermal transport phenomena3. We employ a suite of complementary, all-optical spectroscopic techniques to map phonon behavior over multiple frequency and length scales. Anisotropic thermoreflectance thermometry provides sub-degree angular resolution of in-plane responses4, while polarized, angle-resolved Brillouin light scattering (BLS) probes acoustic phonons to extract the anisotropy of phonon phase velocities5.

Most notably, extreme UV transient grating spectroscopy experiments performed at the FERMI free-electron laser facility enable access to grating spacings as short as 26 nm6. This capability is crucial for isolating phonon contributions with varying mean free paths, including those relevant to nanoscale thermal transport that are elusive in conventional setups. Variation of the nanoscale grating spacing and temperature enables high and low frequency band-pass filtering in the THz regime. Furthermore, the transient responses reveal multiple oscillatory modes - attributable to GHz surface acoustic waves which reveal characteristic anisotropy. To complement our experimental findings, we perform ab-initio Green-Kubo calculations7 and Boltzmann Transport Equation (BTE) simulations to capture non-equilibrium phonon interactions and the interplay between phononic properties and thermal conductivity anisotropy. Our results deepen the understanding of anisotropic thermal transport in transparent conductive metal-oxides and provide guidelines for optimized heat dissipation.

**References**

1 N. C. Passler, et al., *Nature* **602**, 595 (2022).

2 D. N. Basov et al., *Nature Materials* **16**, 1077 (2017).

3 K. Xu et al., submitted to *ACS Nano* (2025).

4 L. A. Perez et al., *Review of Scientific Instruments* **93**, 034902 (2022).

5 B. Graczykowski et al., *Physical Review B* **91**, 075414 (2015).

6 F. Bencivenga et al., *Advances in Physics: X* **8**, 2220363 (2023).

7 F. Knoop et al., *Physical Review Letters* **130**, 236301 (2023).