Quantitative Measurements of Anisotropic Thermal Transport in vdW Materials via Cross-Sectional Scanning Thermal Microscopy (xSThM)

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Nanoscale thermal transport is a key factor limiting the clock speed of computer processors and defining the performance of thermoelectric (TE) materials. While in the former the increase of heat dissipation is essential, in the latter, low thermal conductivity provides a major boost to the TE figure of merit (FoM). The versatility of van der Waals (vdW) materials and their heterostructures, including both the highest known in nature thermal conductivity material (graphene for in-plane heat transport) and one of the lowest conductivity solid-state crystal (cross-plane turbostratic MoS_2), provide an extremely useful toolbox for addressing the control of thermal transport in diverse applications[1]. The challenge nevertheless lies in the difficulty of measuring and quantifying the thermal transport within atomically thin and highly anisotropic vdW materials and between these materials and substrates.

Here we report a novel powerful approach of cross-sectional scanning thermal microscopy (xSThM) for studying anisotropic heat transport in nanoscale layered vdW materials. We use beam exit cross-sectional polishing (BEXP) of vdW nanoflakes shaping these into ultra-thin low angle wedges with atomic-scale surface flatness, followed by the xSThM in high vacuum (HV) conditions. By mapping continuously varying sample thickness of the wedge, we eliminate artefacts of through-the-air heat transport and suppress a generally unknown SThM tip-surface interfacial thermal resistance. By comparing experimental results with the finite element analysis (FEA) simulation and analytical models, we can directly evaluate the anisotropy between the in-plane and cross-plane thermal conductance of the vdW materials ($k_{\parallel}/k_{\perp}$), the local thermal resistance at the vdW material–substrate interface (r_{int}) and the SThM tip-material thermal resistance (R_c).

We apply this approach to quantify the thermal conductivity of gamma indium selenide (γ-InSe) vdW material, which has high potential in TE applications due to its advantageous electrical and thermal properties[2]. Additionally, we employ the same methodology with graphite nanoflakes for reference comparison. We also experimentally study the material-substrate heat transport between the vdW materials and high (Si) and low (SiO_2) thermal conductivity substrates. xSThM allowed us to independently confirm the heat transport anisotropy and anomalous low thermal conductivity values of $k_{\parallel} = 4.956$ $Wm^{-1}K^{-1}$ and $k_{\perp} = 0.2402$ $Wm^{-1}K^{-1}$ for γ-InSe on SiO_2, also extracting the interfacial thermal resistance between γ-InSe and SiO_2 ($r_{int} = 1.236 \times 10^{-9}$ Km^2W^{-1}). The γ-InSe on Si data indicate the same type of heat transport anisotropy but provide slightly different absolute values, presumably due to ballistic heat transport in Si on the length scales involved, requiring different analysis which is underway. Our results support the potential of γ-InSe as a high TE efficiency material, where the low thermal conductivity values can be combined with a high power factor, ultimately enhancing the FoM.

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