Measurements of nanoscale thermal transport and its anisotropy in vdW materials via cross-sectional scanning thermal microscopy (xSThM)

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Summary

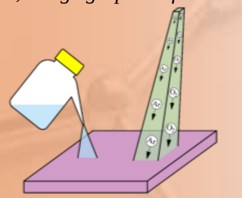
We present a novel cross-sectional scanning thermal microscopy (xSThM) approach to study anisotropic heat transport in nanoscale vdW materials (γ-InSe and graphene) and thermal resistances of vdW – substrate interfaces. We use beam exit cross-sectional polishing (BEXP) of vdW nanoflakes which shapes 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, we eliminate artefacts of through-the-air heat transport and SThM tip-surface interfacial thermal resistance[5], also quantifying the vdW material-substrate heat transport by depositing vdW materials on high (Si) and low (SiO_2) thermal conductivity substrates. By comparing experimental results with the theoretical model[5], we can directly access the anisotropy of in-plane and cross-plane thermal conductance of the vdW materials ($k_\parallel/k_\perp$) and thermal resistance (r_{int}) at the vdW material – substrate interface.

Introduction

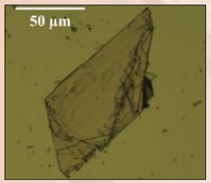
Thermal transport is one of the key factors in defining the performance of thermoelectric (TE) materials, given that most of these cannot combine high power factor with low thermal conductivity[1]. Nevertheless, thermal transport in van der Waals (vdW) materials and their heterostructures could be tweaked, leaving an open platform for new TE applications[2]. In particular, indium selenide (InSe) shows high TE potential due to advantageous electrical and thermal properties, increasing the TE efficiency[3]. Here we quantify the thermal transport in γ-InSe nanolayers via x-section scanning thermal microscopy (xSThM), providing a key insight to its in-plane and cross-plane thermal conductivities as well as interfacial thermal resistance to the substrate[4,5].

Fabrication

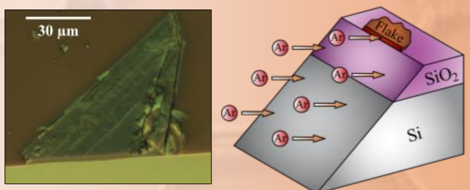
Samples: *wedge γ-InSe flake on Si, wedge γ-InSe flake on SiO_2 + Si, wedge graphene flake on Si, wedge graphene flake on SiO_2 + Si*. The fabrication procedure is depicted as follows:



1. Substrate cleaning: Solvent cleaning + O_2/Ar plasma on surface.



2. Exfoliation: vdW flakes deposited by dry exfoliation near to the substrate's edge.

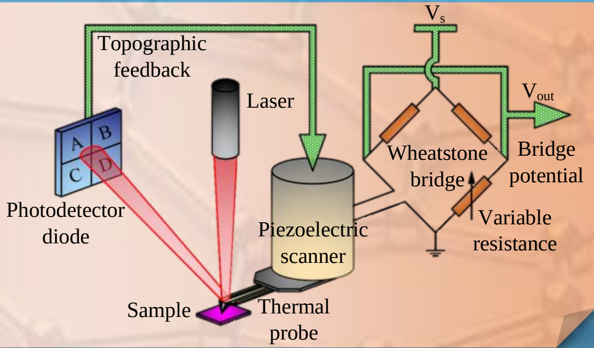


3. BEXP: Cross-sectional wedge cut + polishing of substrate's edge and flake.

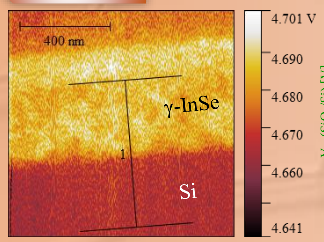
Characterization

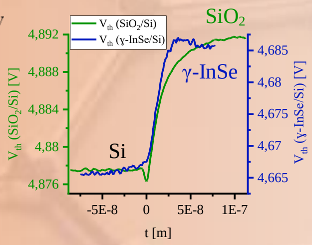
HV-SThM (see scheme on the right) measurements were performed with an NT-MDT Smena microscope under high vacuum conditions (≈ 10^{-6} mbar) and ambient temperature (≈ 296 K).

SThM incorporates a resistive heater receiving constant power via a DC-AC Wheatstone bridge. The bridge output voltage is proportional to the probe temperature, which changes due to variations of the probe-sample heat flow. By moving the probe across the sample surface, a quantitative map of the sample heat transport is obtained.



Results





Thickness (t) and thermal signal (V_{th} - *left image*) maps of the wedge 2D material/substrate and Si/SiO_2 interfaces are obtained on all the samples. Profiles (*right graph*) are extracted from the images to provide the quantitative experimental data that are compared with the theoretical model.

We can also obtain the approach/retract curves of the thermal signal to measure the contact (V_{th}) and non-contact (V_{nc}) voltages. The probe thermal resistance (R_p) is calculated by calibration. The thermal resistance (R_x) is then obtained:

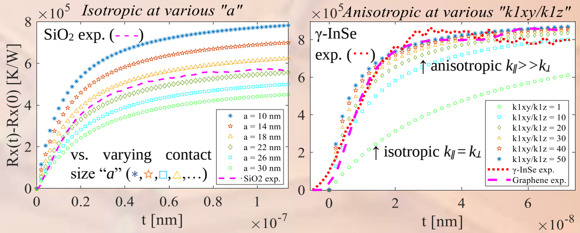
$$R_x = C_{cor}\frac{R_p V_{th}}{V_{nc} - V_{th}} \quad (1)$$

C_{cor} is the correction of tip-end vs. average tip temperature. The measured R_x depends on the tip-surface contact and sample spreading resistance:

$$R_x = R_s + R_c \quad (2)$$

Eq. (3) is an isotropic model for heat spreading[5]. This can be transformed into anisotropic by changing $t \to \bar{t} = t/\sqrt{k_{1,z}/k_{1,xy}}$ and $k_1 = \sqrt{k_{1,xy}k_{1,z}}$. The simulation suggests an anisotropic nature of γ-InSe thermal transport, whereas fitting $R_x(t)$ allows to quantify the thermal anisotropy ($k_\parallel/k_\perp$) and r_{int}.

$$R_x(t) = \left\{\frac{1}{\pi k_1 a}\int_0^\infty \left[\frac{1 + Ke^{\frac{-2xt_{eff}}{a}}}{1 - Ke^{\frac{-2xt_{eff}}{a}}}\right] J_1(x)\frac{\sin(x)dx}{x^2}\right\} + R_c \quad (3)$$



Conclusions:

- xSThM allows to assess thermal transport in nanoscale thick vdW materials and heterostructures.
- We independently evaluate the vdW material and material – substrate interfacial thermal resistance.
- We show that the anisotropy of thermal conductance in nanoflake is reflected in the xSThM response vs. thickness with anisotropy of the heat transport in γ-InSe nanoflakes directly observed for the first time.

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