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Mapping Nanoscale Thermal Gradients in MoS_2 using Plasmon Energy Shifts

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In modern microelectronic devices both ballistic and diffusive thermal transport are important because their critical dimensions are smaller than a typical phonon's mean free path. Directly measuring temperature with nanometer spatial resolution will help characterize the thermodynamics in these devices [1]. Here we use plasmon energy expansion thermometry (PEET), a non-contact thermometry technique, to probe the sample's temperature without interference [2]. Like aluminum [2] and silicon [3], the MoS_2 bulk plasmon shifts due to the density changes from thermal expansion [4]. PEET translates these shifts in the bulk plasmon energy to changes in temperature. This technique provides a method for in-situ temperature measurements with nanometer-scale resolution.

Here we show how measurements of in-plane temperature gradients across suspended few-layer MoS_2. We induce a temperature gradient by independently Joule heating microheaters on either side of the suspended sheet, as shown in Figure 1. A plasmon energy map is constructed by acquiring electron energy loss spectrum images across the MoS_2 and the curve fitting both the ZLP (Gaussian fit function) and plasmon peak (Lorentzian fit function) to precisely measure shifts at the parts-per-thousand level across the device. The fit regions are shown in Figure 1-C. The temperatures are determined by using the bulk thermal expansion coefficient of MoS_2 to connect the changes in density observed in the plasmon shift to changes in temperature.

A plot of the relative plasmon energy shift for different materials is shown in Figure 2. The plasmon energy maps from the spectrum image have been converted to line profiles by averaging the short direction of the scan (see Figure 2-B). The plasmon energy shifts are small, only at the few parts-per-thousand level over the two-micron length of the trench. These shifts are smaller than those observed in aluminum, but are larger than those observed in Silicon, given a similar change in temperature, due to the respective difference in thermal expansion (See Figure 2-A). Converting the plasmon energy shifts to temperature we see that there is a gradient across the device of about 100 K/µm. The device shown in Figure 2-B has been milled using a helium ion microscope. We have milled the device to show how it is possible in principle to constrain the heat flow by creating narrow channels [5].

References:

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[5] We acknowledge the assistance of Matthew Hunt from the Kavli Nanoscience Institute at Caltech in using the Zeiss Orion NanoFab Helium Ion Microscope to mill our sample. We acknowledge the support of the Center for Electron Microscopy and Microanalysis (CEMMA) at the University of Southern California

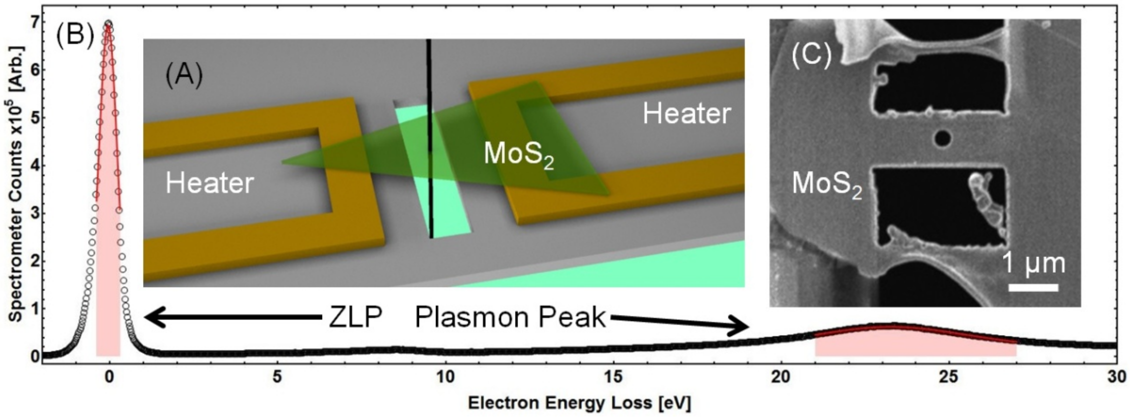

Figure 1. (A) Cartoon showing the location of the two opposing heaters relative to the suspended MoS_2 sheet (here the TEM's electron beam is shown as a black verticle line). (B) A representative low loss EELS spectrum from a spectrum image. Both the ZLP and plasmon peak are fit (red lines) and the region of the fit is shown shaded red. (C) The milled MoS_2 sheet suspended over a trench cut into the silicon chip supporting the sample and heaters.

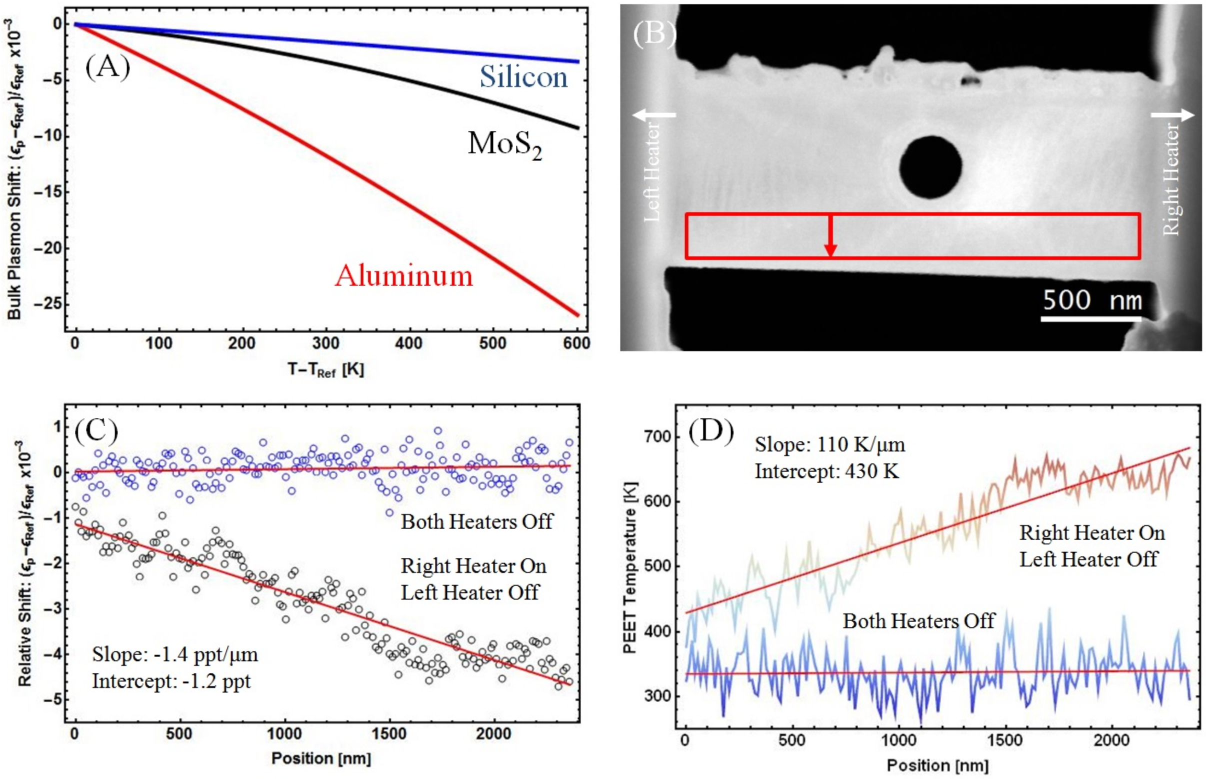

Figure 2. (A) Bulk plasmon shifts as a function of temperature for silicon, MoS_2, and aluminum determined from the literature values of the temperature dependent thermal expansion coefficient. (B) Helium ion microscope image of the suspended MoS_2 flake. The red box shows the acquisition region for a spectrum image. The red arrow shows the averaging direction. (C) Plot of relative shift in plasmon energy as a function of position with the heaters off (blue) and the right heater on (black). (D) Temperature line profiles determined by the relative shift in the plasmon energy and the bulk thermal coefficient of expansion in MoS_2.