Nanoscale thermal metrology using electrons and photons

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We are interested in developing new techniques for heating and measuring temperature at the sub-100 nm scale, especially using non-contact methods. I will briefly introduce several recent and ongoing efforts in this direction with various collaborators.

Quantifying e-beam heating in a TEM: With its 68°C phase transition temperature and known thermal conductivity, a cantilevered VO_2 nanoribbon can act as a binary thermometer and heat flow sensor. We used this configuration inside a TEM to measure the heat deposited by a 300 kV e-beam into a VO_2 nanoribbon (thickness 240 nm) and a silicon nanowire (diameter 630 nm), finding net heating efficiencies per incident electron of 200 eV and 110 eV, respectively [1]. For typical beam currents this corresponds to 0.5 to 3 μW of heating.

Thermometry using a single photoluminescent nanoparticle: We recently demonstrated far-field optical thermometry of individual lanthanide-doped inorganic nanoparticles ($NaYF_4$:Yb,Er) as small as 20 x 20 x 40 nm^3 [2, 3]. These particles have excellent uniformity, allowing isolated particles to be identified from their brightness using only optical imaging. These same particles are also amenable to thermometry using cathodoluminescence [4], the emission of light in response to an e-beam excitation.

Thermometry using thermal diffuse scattering in a TEM: The Debye-Waller factor describes how the random thermal jiggling of an atomic lattice smears out the resulting diffraction pattern. Thus, measuring the diffuse background of a diffraction pattern between its Bragg spots can be the basis for a thermometry [5]. We are pursuing this in a scanning TEM [6].

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[2] J. D. Kilbane, A. Pickel *et al*., "Far-field optical nanothermometry using individual sub-50 nm upconverting nanoparticles," *Nanoscale* **8**, 11611 (2016).

[3] A. Pickel, poster at the 9th US-Japan Joint Seminar on Nanoscale Transport Phenomena (2017).

[4] C. Aiello, A. Pickel *et al.*, in preparation (2017).

[5] L. He and R. Hull, "Quantification of Electron-phonon Scattering for Determination of Temperature Variations at high Spatial Resolution in the Transmission Electron Microscope," *Nanotechnology* **23**, 205705 (2012).

[6] G. Wehmeyer, poster at the 9th US-Japan Joint Seminar on Nanoscale Transport Phenomena (2017).