

## Improved Temperature Determination from Plasmon Energy Shifts in Aluminum

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On macroscopic length scales temperature measurements are made using thermocouples, using optical pyrometers, and by detecting infrared radiation. These methods are not scalable to microelectronic device scales, such as the 22 nm gate width in modern transistors. Temperature measurements at these length scales characterize a device's heat generation, a characterization which is important for improving energy efficiency [1]. Different methods are used on these sub-micron scales, principally measurements of the Debye-Waller factor [2], extended electron-energy loss fine structure [3], and thermal expansion [4,5]. Here we describe an improved method for measuring the thermal expansion of materials, and thus their temperature, at small length scales. As a demonstration we apply the method to an aluminum TEM sample and compare the results with the temperature measured with a thermocouple attached to the heating sample holder.

The thermal expansion of solids changes the separation between nuclei and the density of valence electrons. Nuclei separation is typically measured through electron diffraction, and the density of valence electrons through electron energy loss spectroscopy (EELS). Using the zero loss peak (ZLP) as a reference, the plasmon energy can be precisely determined through the difference of the plasmon peak and ZLP positions. As the density of valence electrons changes due to the thermal expansion of the solid, so does the separation between the plasmon peak and ZLP. A precise determination of these peak positions can be used to measure the thermal expansion in a material.

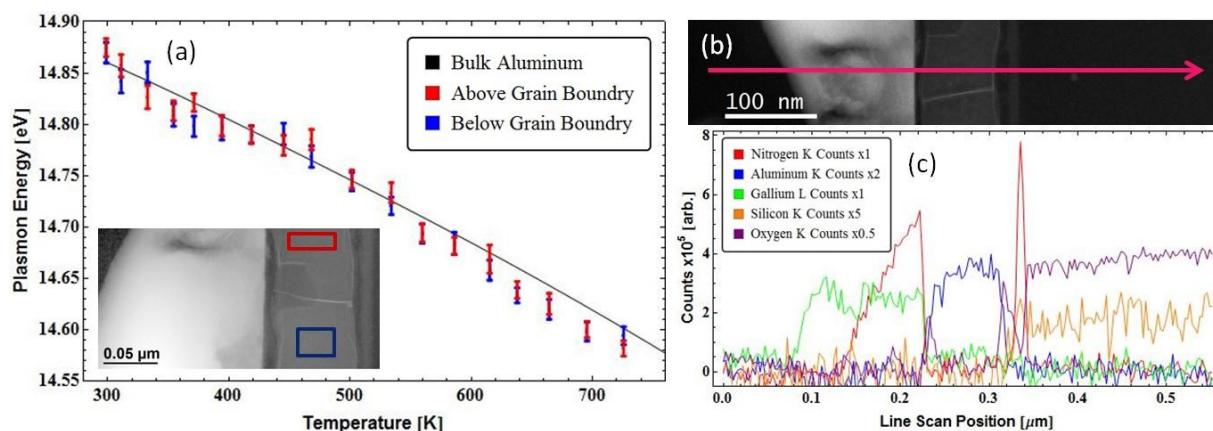
Peak positions determined by finding the highest intensity pixel have an energy resolution limited by the pixel width, typically 0.03 eV/pixel or 0.05 eV/pixel. An improvement can be made by fitting the peaks. This method uses the relationship between many pixels near the peak to determine the maximum value more precisely than the width of a single pixel. Fitting gives a factor of 3 improvement relative to the spectrometer's dispersion, thereby improving the energy resolution from 30 meV to 10 meV. Figure 1a shows the use of curve fitting to improve the precision of the measurement of the aluminum plasmon's energy shift relative to the ZLP as a function of temperature (The composition of the focused ion beam prepared cross section is shown in Figure 1b and Figure 1c.). The plasmon energy shifts are in good agreement with the predicted plasmon energy shifts determined from bulk thermal expansion of aluminum [6].

Improved plasmon peak determination can be extended to the analysis of plasmons in heterogenous samples. Figure 2 shows a selection from a stack of spectrum images that were acquired at different temperatures. The spectrum images' plasmons were fit not using fixed fit windows, as in Digital

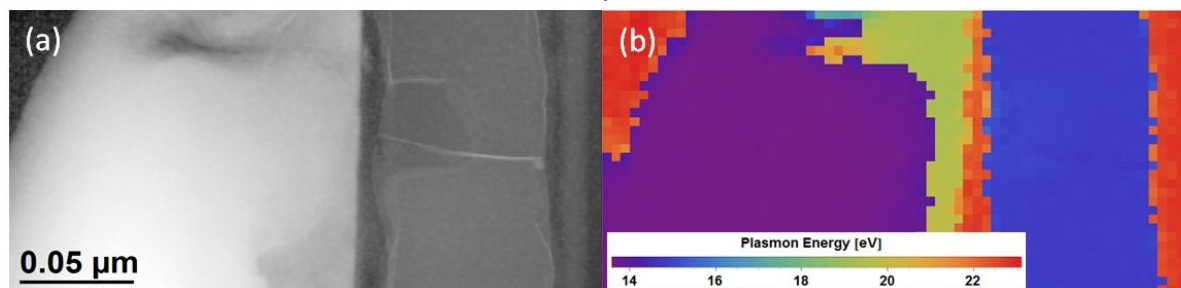
Micrograph's non-linear least squares algorithm, but instead by finding the plasmons peaks and adjusting the fit region to minimize the fit residuals. Such adaptive windows produce a plasmon energy map with improved precision and capable of covering a wide range of plasmon energies.

#### References:

- [1] D Cahill *et al*, 2002, Thermometry and Thermal Transport in Micro/Nanoscale Solid-State Devices and Structures, ASME Journal of Heat Transfer, **124**, (2002), p. 223.
- [2] B Shevitski *et al*, Dark-field transmission electron microscopy and the Debye-Waller factor of graphene, Phys. Rev. B, **87** (2012), p. 045417.
- [3] M M. Disko *et al*, Temperature dependent transmission extended electron energyloss fine structure of aluminum, J. Appl. Phys. **65**, (1989), p. 3295.
- [4] P Palanisamy *et al*, Melting and supercooling studies in submicron Al particles using valence electron energy-loss spectroscopy in a transmission electron microscope, J. Appl. Phys. **110**, (2011), p. 024908.
- [5] S K. Eswara Moorthy *et al*, Temperature dependence of the plasmon energy in liquid and solid phases of pure Al and of an Al-Si alloy using electron energy-loss spectroscopy, J. Appl. Phys. **110**, (2011), p. 043515.
- [6] J C. Wilson, The thermal expansion of aluminium from 0° to 650° C, Proc. Phys. Soc. **53**, (1941), p. 235.



**Figure 1.** (a) Aluminum plasmon energy at different temperatures. The inset shows the regions from which the mean and standard deviations were determined. (b) Dark field image and arrow showing the location from which the EELS core loss was acquired. (c) Core loss integrated signal from the indicated region in (b). The regions containing Ga, GaN, Si<sub>x</sub>N<sub>y</sub>, Al, and SiO<sub>z</sub> are evident.



**Figure 2.** (a) Dark field image acquired simultaneously with the spectrum image, (b) The plasmon energy map was determined by fitting both the zero loss peak and plasmon peak. The temperature at which this map was acquired was 299.3 K. Maps were acquired from 300-730 K in ~30 K intervals.