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Investigation of Electron-Phonon Scattering for High Spatial Resolution Temperature Measurement

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This work investigates the possibility for nanoscale temperature measurement using electron-phonon thermal diffuse scattering (TDS) in transmission electron microscopy (TEM). Our observations of TDS intensity for (100) single crystal Si and Ge show interdependences of temperature and sample thickness which can be understood through angular distributions of electron-phonon scattering as a function of temperature. The temperature sensitivity of the integrated TDS intensity can be relatively high at greater than one part per thousand per ºK temperature difference, e.g., 1.5×10^{-3} K^{-1} for 55 nm thick Si from 30 - 200 ºC integrated over reciprocal lattice lengths of 1.3-1.5 $Å^{-1}$ from the (000) beam. This shows that measurement of TDS intensity in the TEM is a promising means for nanoscale temperature measurement; our measurements to date indicate that temperature changes less than 10 K are detectable.

The average diffraction intensities with respect to reciprocal distance from the (000) beam was calculated from multiple experimental diffraction patterns. Figure 1 shows the result for a 55 nm thick Si sample with the electron probe about 650 nm in diameter. Diffraction intensities normalized to the room temperature value in Fig. 1(b) clearly show the increase of TDS intensity and decrease of Bragg peak intensity (signified by the local minima at the Bragg peaks) with temperature. Results of Si and Ge diffraction at different sample thicknesses are summarized in Fig. 2. The rate of change, dI/dT, is relatively insensitive with sample thickness. However the normalized rate of change, dI/(IdT), decreases with thickness. For the Ge sample thicknesses of 35 nm and 175 nm, a decrease in TDS intensity Ge over the range of 0.9-1.1 $Å^{-1}$ with increased temperature was observed.

This indicates that increasing temperature, while inherently intensifying phonon scattering in nature, also results in electrons being scattered at larger angles so that the counts of electrons scattered through smaller angles correspondingly decreases. Theoretical studies by Humphreys and Hirsch reported that TDS adsorption drastically increases at large scattering angles (above 1.2 $Å^{-1}$, 44 mrads for Si and 1.6 $Å^{-1}$, 59 mrads for Ge at 100 keV electron energy) [1]. If electrons undergo multiple phonon scatterings and scattering angle further increases, they may exceed the collection angle of TEM (within about 3 $Å^{-1}$, 75 mrads in our experiments). Future experiments with high-angle annular dark-field imaging may help further elucidate the relationship between the TDS intensity and diffraction angles, and further improve the temperature sensitivity of our TDS measurements.

In summary, we systematically investigated thermal diffuse scattering of electrons in Si and Ge as functions of temperature and sample thickness. Our results indicate that potential nanoscale temperature measurements using TDS of electrons in the TEM need to be "tuned" (in sample thickness and collection angle) for greatest sensitivity for a particular material. Our initial experiments have revealed temperature sensitivities > 1×10^{-3} K^{-1} for TDS intensities. This implies the ability to measure local sample temperature (or, at least, local sample temperature changes) of less than 10 K [2].

References

[1] C.J. Humphreys et al., *Philos. Mag.* 18 (1968) 115.

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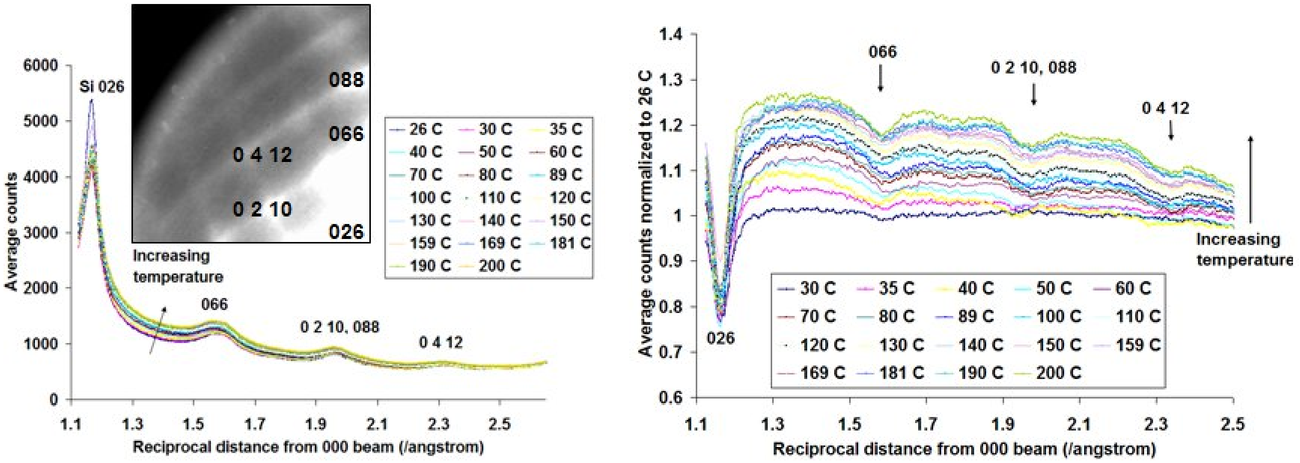

(a) (b)

FIG. 1. (a) Average diffraction intensity with respect to reciprocal distance from the (000) beam for a 55 nm thick Si sample. Inset is the diffraction pattern with Bragg reflections indexed. (b) Diffraction intensity normalized to 26 ºC.

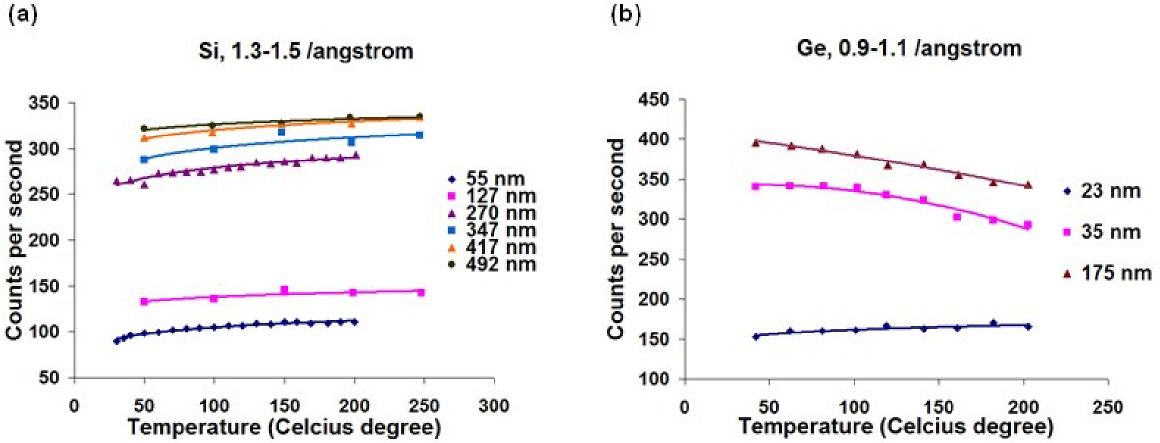

FIG. 2. Average diffuse scattering counts per second (using count rates here because different acquisition times were used for measuring samples of different thickness) of (a) 1.3-1.5 $Å^{-1}$ in Si diffraction and (b) 0.9-1.1 $Å^{-1}$ in Ge diffraction from 30 ºC to 200 ºC. Legends show different sample thicknesses.