Nanoscale Thermal Imaging Microscopy of Thermoelectric Devices

P. Mayer, R.J. Ram
Sponsorship: ONR MURI

In many solids, a change in temperature produces a small change in the dielectric response of the material, and particularly in the index of refraction. By measuring the change in reflectance from a device or material whose temperature is modulated in some way, an image of the temperature change can be obtained, after proper calibration. This approach is useful for examining heat transport in electronic/optoelectronic devices since the heating due to a changing bias current or voltage can be measured. Unlike the case with typical (infrared) thermal imaging, deep sub-micron spatial resolution is possible. Shown below in Figure 1 are (uncalibrated) thermoreflectance images of the Joule and Peltier heating and cooling in a 4.9 μm-thick InGaAs-based superlattice incorporating semimetallic self-assembled ErAs nanodots, on an InP substrate. The ErAs dots and the superlattice both scatter phonons participating in cross-plane heat transport, reducing the thermal conductivity to below the alloy limit by nearly a factor of two. The dots and the superlattice are also expected to increase the free electron concentration, the electrical conductivity, and the Seebeck coefficient.

The thermal imaging technique used here relies on a CCD camera triggered 4 times per temperature cycle and averaged over many cycles, so that each pixel of the camera functions as a lock-in detector. Because the change in reflectance is small (e.g. 1 part in 10000, per degree Kelvin) it has been suggested that the temperature resolution of the technique is limited by the least significant bit size of the quantizer of the CCD array, giving rise to a minimum temperature resolution in the single Kelvin range. However, due to the presence of noise in the pre-quantized signal, sufficient averaging can actually improve the resolution. We have demonstrated a temperature resolution on the order of 10 mK and developed a quantitative theory describing the statistics and accuracy of the measurement, set by the noise characteristics of the camera and the measurement characteristics. Figure 2 shows the measurement of a temperature signal smaller than that corresponding to the bit size of the CCD array, as a function of the measurement duration. The theoretically predicted mean and standard deviation are close to those measured.

▲ Figure 1: Cross-plane magnitude and phase images of the Joule and Peltier contributions to the thermal response in a nanostructured thermoelectric element. Superlattice (clearly visible in the top photomicrographs) is to the left of the image.

▲ Figure 2: Measurements (gray) and theoretical predictions (black) for sub-quantization thermoreflectance measurements. The measurement converges for sufficient iterations (long-enough duration).