Measuring Thermal and Thermoelectric Properties of Single Nanowires and Carbon Nanotubes

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Knowledge of nanowire and carbon nanotube thermal and thermoelectric properties will be important for the thermal management of nanoscale devices that have recently been demonstrated (optoelectronic, sensing, and computing) and essential for the design of nanostructured thermoelectric materials. For nanowire diameters smaller than the bulk mean-free path of heat carriers (electrons and/or phonons), theory predicts that the thermal conductivity of these structures will be reduced when compared to similar bulk materials [1]. In order to experimentally verify these predictions, we are exploring several systems to measure the properties of single nanowires and carbon nanotubes.

Current work includes a basic platform to measure the thermal conductivity and specific heat of electrically conductive nanowires, such as the silicon nanowire shown below. Electron-beam lithography was used to pattern the leads of a four-point probe aligned to the ends of the nanowire. Joule heating of a suspended nanowire with thermally clamped ends results in a temperature rise of the nanowire due to its finite thermal resistance. This temperature rise can be measured by resistance thermometry (again using the nanowire) and used to calculate its thermal conductivity and specific heat. This technique is being adapted for an in situ TEM measurement, to enable high-throughput physical property measurements of many nanowires of various geometries and morphologies, and allow correlations with their atomic structure as determined by TEM.

Microfabricated metal lines can also be employed to measure electrically insulating nanowires. Using electron beam lithography, a metal heater line is fabricated such that a target nanowire crosses the center of the line. With the ends of the nanowire and heater thermally anchored, the nanowire removes a fraction of heat from the heater line, reducing the heater’s temperature rise, and thus making it possible to calculate the thermal resistance of the nanowire.

Figure 1: Contacts for a four-point probe measurement of a single silicon nanowire.

REFERENCES

Nanocomposites as Thermoelectric Materials

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Direct energy conversion between thermal and electrical energy based on thermoelectric effects is attractive for potential applications in waste heat recovery and environmentally-friendly refrigeration [1-2]. The energy conversion efficiency depends on the dimensionless figure of merit of the thermoelectric materials, ZT, which is proportional to electrical conductivity, square of the Seebeck coefficient, inverse of the thermal conductivity, and absolute temperature. At the current stage, the low ZT values of available materials restrict the efficient applications of this technology. Recently, significant enhancements in ZT were presented through the use of nanostructures such as superlattices. Previous works done by our group show that such improvement in superlattices is mainly attributed to the increased interfacial diffuse phonon scattering [3-4]. These studies lead us to pursuing the nanocomposite approach as a cost-effective alternative in developing high ZT materials.

Previously, we reported thermal conductivity reduction in SiGe nanocomposites. Through collaboration with Boston College group and Jet Propulsion Lab, we realized significant improvement in the ZT over that of SiGe used in the past NASA flights (Figure 1). We are also working on Bi$_2$Te$_3$ and PbTe nanocomposites. Our preliminary results on Bi$_2$Te$_3$ nanocomposites also show reduced thermal conductivities. Work is in progress to optimize the structures for further improving the ZT values.

![Figure 1: Measurements of temperature-dependent ZT. Nanostructured sample SGMA04 shows higher ZT than typical bulk alloy, “RTG SiGe.”](image1)

![Figure 2: Temperature-dependent thermal conductivities of Bi$_2$Te$_3$ nanocomposite samples. Data of bulk materials are plotted for comparison.](image2)

REFERENCES