Thermal Conductivity Measurements on Highly-Dense Forest of Nanowires

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Thermal conductivity in semiconductors is dominated by phonons that have a broad spectral distribution at room temperature. The rate of Umklapp processes dominates the phonon scattering at room temperature; it scales with ω^2 (ω is the phonon frequency). This implies that low frequency acoustic phonons will have longer mean free path that can be reduced by rational incorporation of phonon scattering elements. For instance, when the dimensions of the material are comparable to the mean free path of the phonons, the thermal conductivity drops down significantly due to surface scattering mechanism. In this work, we have fabricated an array of nanowires (silicon and various bismuth telluride) in nanoporous alumina templates with very high nanowire density ($\approx 10^9/cm^2$). We have employed 3ω method and Raman thermometry to extract the thermal conductivities of the nanowires. Both methods are often employed with a simplified approximation and this, in turns, brings several limitations on its applicability especially in the case of thin nanoporous material. For using it in our case in 3ω method, we have developed a model using an analytical solution of 2D heat conduction on a multilayer system to extract the thermal conductivity of the whole array of nanowires embedded in porous alumina which is an anisotropic film. Fitting of the experimental data with the model considering all the different layers on the sample is done to extract the correct value of thermal conductivities of the embedded nanowires. The variation in thermal conductivities as a function of temperature (ranging from 80 K to 350 K) has been obtained. The results are correlated with the geometry (roughness) and composition of the nanowires. High-resolution TEM imaging along with the compositional analysis with EDX gives an insight of the variation in phonon transport. The difference in thermal conductivities between nanowire and bulk is significant in silicon showing a strong confinement effect in silicon. A thermal conductivity around 10 W/mK is observed in 60 nm diameter nanowires. The thermal conductivity is reduced with the reduction in nanowire diameter, which shows stronger confinement in thinner silicon nanowires. Comparison of the thermal conductivity in between silicon and ternary alloys of Bi_2Te_3 with reduction in dimensions is clearly interpreted. By analysing the different parameters (Seebeck effect, electrical conductivity etc.), it can be seen that the array of highly-doped thin nanowires of silicon would result in highly-efficient building blocks for innovative thermoelectric devices.