Influence of size and roughness on the thermal conductivity of free-standing Si membranes investigated using 2-laser Raman thermometry

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A precise determination of the thermal conductivity (κ) of a given material is usually a difficult task since the heat per unit time flowing in a certain spatial direction ($Q \equiv P_{abs}$) must be precisely determined. Contrary to the analogous case of electrons (or holes) propagating in a metal, where the electric current can be easily measured using a galvanometer in the magnetic field created by the current, there is no direct method to measure heat currents. Instead, the heat flux per unit time is usually inferred considering the geometry of the system and the excitation source; the temperature gradient ($\partial T/\partial r$) is measured in the heat flow direction and, finally, the thermal conductivity is obtained through Fourier's law [$\kappa = P_{abs}/(\partial T/\partial r)$]. Several electrical and optical techniques have been developed to measure the thermal conductivity of a large variety of materials and structures. Optical methods have recently attracted considerable attention since most of them are contactless and, thus, require little or no sample preparation.

Here, we investigate the thermal properties of free-standing Si membranes [1] in the range between 9 and 1000 nm in thickness using a novel optical contactless technique recently developed for such purpose: 2-laser Raman thermometry (2LRT) [2]. We compare the results with those obtained using a one-laser version of this technique commonly known as Raman thermometry [3], and show the advantages provided by the 2LRT, e.g., improved accuracy and direct access to the temperature distribution with respect to a localized thermal excitation. As an excellent example of the potential of this approach we show how the thermal conductivity of ultrathin Si membranes is strongly influenced by the presence of the silicon native oxide. A three-fold reduction in the thermal conductivity is found to arise only from the formation of such oxide. In addition, we have also investigated the influence of thickness and surface roughness in the spatial decay of the thermal field. In the purely diffusive case the thermal field decays logarithmically in two dimensions following Fourier´s law, $T\ \alpha\ \ln(r)$, as we have observed for membranes thicker than 100 nm at room temperature. Surprisingly, thinner membranes exhibit deviations from this behaviour, which we explain with a phenomenological model taking into account the dependence of the specularity parameter on the wavelength of the thermal phonons.

References:

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