Thermal conductivity measurements using resistive scanning thermal micro and nanoprobes

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By nanostructuring materials their physical properties can be engineered to achieve optimal performances, in particular their thermal properties. Examples include materials used in renewable energy generation (thermoelectricity, photovoltaics) and structural composites. It happens that the flow of heat at the nanoscale is completely different from that experienced in macroscopic systems. Indeed, the dominant phonon wavelengths at room temperature are of order of a nanometer with mean free paths extending from nanometers to micrometers depending on the material and on the energy carrier (electron, phonon, etc.). Accordingly, heat dissipation in solids ceases to be entirely diffusive at the nanoscale. As a consequence, the usual methods for modelling macroscopic thermal transfer are completely inappropriate. Regarding available thermal measurement methods those based on optical effects such as infrared thermal emission or sensing, Raman spectroscopy or photo-reflectance are limited to spatial resolution of the order of 500 nm or greater. Scanning Thermal Microscopy (SThM) is a key technique for thermal measurements developed on scanning probe microscopy. Due to the high spatial resolution enabled using thermal nanoprobes this microscopy has already been applied in various fields of science and engineering since the 1990s. However it remains highly non-quantitative in normal use [1-4]. There is a need for a complete and accurate thermal measurement methodology, which is the aim of this work.

For three resistive SThM probes with different sizes and sensor materials (Wollaston-wire microprobe, palladium nanoprobe and doped silicon nanoprobe) we developed calibration methodologies for thermal conductivity local-point measurement. Specimens of well-known thermal conductivities and surfaces controlled in terms of roughness and nanomechanical properties are used as reference materials. In order to better understand the tip-sample thermal interactions and also identify the best measurement environmental conditions, two different surrounding environments, ambient and vacuum, were considered. Our final methodology includes additional steps compared with usually used approaches, enabling to correct the thermal drift occurring in such experiments, deal with uncontrolled perturbations due to the laser irradiation on the cantilever and probe, and detect any change of the tip apex due to a deformation or a contamination. Its application allows us to clearly confirm that thermal-conductivity measurements with SThM are limited to low thermal conductivity materials, as shown by figure 1. Ultimately, results are also shown to be strongly dependent on the environment and on the kind of probe used. We find that reducing the probe size induces an increase of sensitivity of the technique to the tip-sample contact physical parameters (e.g. roughness, thermal boundary resistance, surface state). Key parameters of the probe-sample interaction are identified using an analytical modelling accounting for size effect. Their contributions in the measurement are discussed in details.

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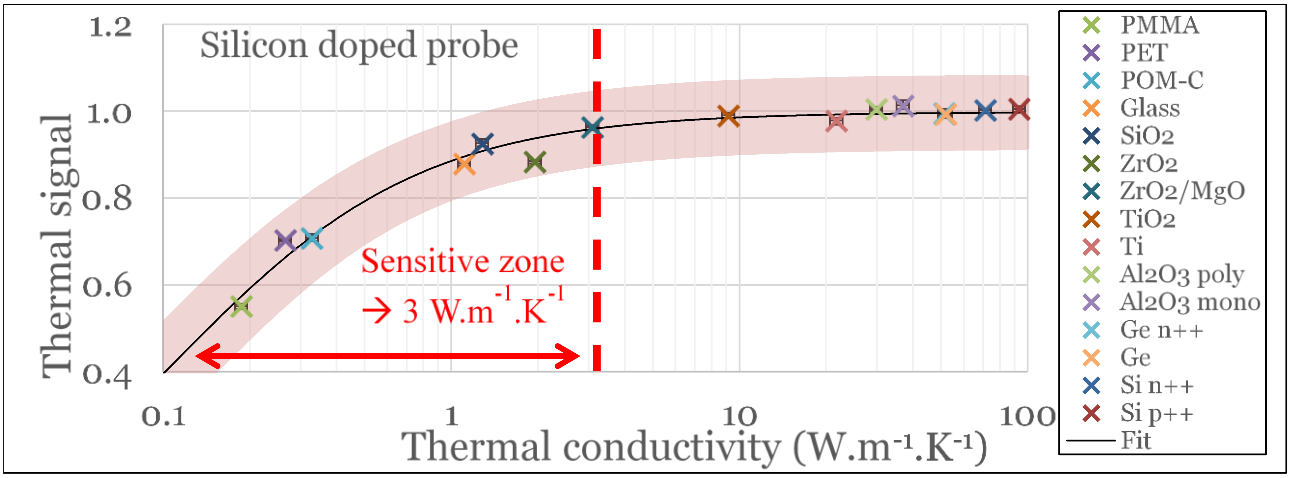

Figure 1: Calibration curve for doped silicon nanoprobe