Scanning Thermal Microscopy: unraveling and mapping thermal phenomena at the nanoscale

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Abstract

There has been growing interest in obtaining greater knowledge on heat transport phenomena in nanostructured materials, since they are often determinant for the performance of modern micro and nano-devices, such as sensors possessing nano-sized features and thermoelectric nanomaterials. Furthermore, nanoscale thermal properties assume great relevance in modern electronic circuits that dissipate power at the nanoscale.[1] Scanning thermal microscopy (SThM) is a powerful tool with a leading role concerning probing and mapping of local thermal properties of materials and heat generation with nanometric spatial resolution. Based on an atomic force microscope (AFM), the SThM uses a specialized heated thermal probe designed to act as a thermometer instead of the conventional AFM tip. Since its invention, AFM revealed itself a fundamental mean for imaging and introducing features at the nanoscale that alter the structure and properties of the materials. Enabling self-heating on a conventional AFM tip paved the way for its implementation, in the form of Scanning Thermal Microscopy, not only in a wide variety of manufacturing and imaging applications with unmatched quality, but also as a leading technique in the search for thermal functional properties. Determining and acting on the thermo-physical properties of microstructures is thus of great use in understanding/modelling heat transfer and macroscopic properties of heterogeneous materials. As an example, the study of contrast thermal properties is especially important for the study of polymer composites and lithographed materials.

The fundamental feature of this technique, the SThM tip, is a nanofabricated thermal probe that can act as a resistance thermometer or a resistive heater, depending on the selected operation mode: passive mode or active mode, also known as temperature contrast mode (TCM) and (thermal) conductivity contrast mode (CCM), respectively. It is also possible to collect simultaneously surface topography image and thermal image of the samples under analysis due to the independent nature of both AFM and SThM mechanisms in the same equipment (fig. 1).

Here we present exploration routes for the study of phenomena by Scanning Thermal Microscopy. Using a XE7 Scanning Probe Microscope with Scanning Thermal Microscopy from Park Systems [2], in this presentation we show the path for research in relevant topics, namely thermal conductivity of graphene layers deposited on different substrates by conductivity contrast, the electrocaloric or magnetocaloric effects in nanostructured materials. Further work on inducing and studying structural phase transformations on thin films of functional materials with relevant properties for application in nano-devices, such as $BaTiO_3$ and Ni_2MnGa is also presented. Work in progress for this technique includes also its application to time dependent processes, bringing it forward as a contribution to otherwise complex analysis of dynamic processes.

Due to its high thermal conductivity and subsequent efficiency in heat conduction, graphene is noted as suitable candidate to aid overcome the obstacle of increasing dissipation power density arising from constant downscaling of electronic devices. In fact, graphene's excellent thermal properties, combined with highly interesting electronic and optical properties, recommend it for a wide range of applications in several fields. [3.] However, the mechanisms behind graphene's thermal properties still lack clarity. It has been shown that graphene monolayers possess high thermal conductivity, but the values obtained so far seem to vary according to the deposition method and measurement technique. SThM presents itself as a reliable technique to clarify the intriguing thermal properties of graphene monolayers (fig. 2), namely by enabling accurate estimation of the thermal conductivity of this material supported by different substrates, relying on thermal contrast between the graphene monolayer and other materials with known thermal conductivity [4].

The electrocaloric (EC) effect consists in the variation of temperature that some materials experience under an applied electric field, which is enhanced at temperatures near ferroelectric phase transitions. [5] This is why EC is becoming an interesting alternative to refrigeration based on the magnetocaloric effect due to the economically inviable large magnetic fields that this effect requires. [6][7] Thin films exhibit especially high EC effects. However, direct measuring of EC in thin films is hard to accomplish due to the great difference between heat flow output shown by thin film and substrate. SThM solves this inconvenience, allowing direct measurement mapping of temperature changes in several spots of a thin film, enabling and promoting thus the search for promising materials for micro-scale cooling applications.

References

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Figures

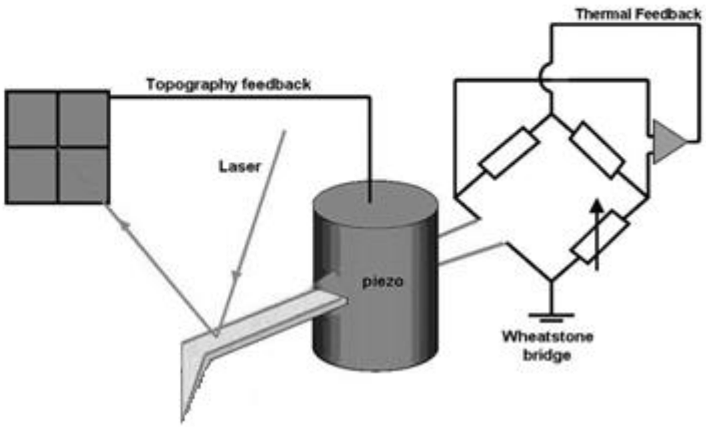

Fig. 1 Schematic showing the independent nature of both mechanisms for topographical and thermal images collection (adapted from Park Systems [2])

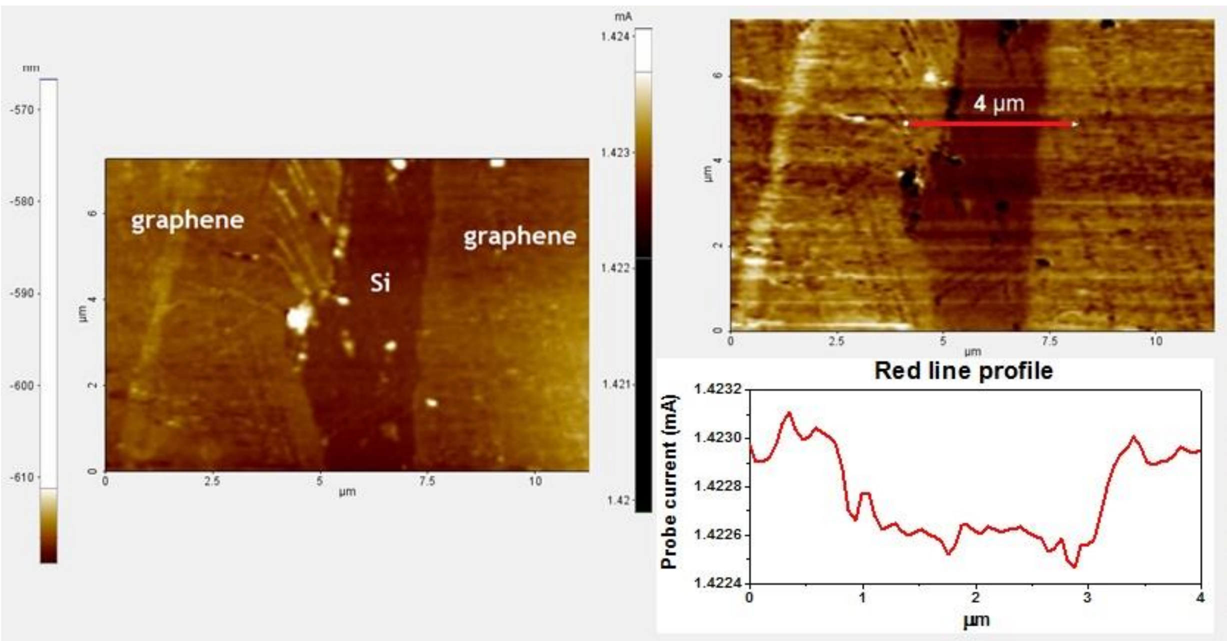

Fig. 2 Left: topographical image of Si/graphene interfaces performed with thermal nanoprobe of SThM system; Right: SThM conductivity contrast image (CCM) of the area depicted on the left and line profile showing the contrast in thermal conductivity between graphene and Si