Nanoscale thermometry using scanning thermal microscopy

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Regions of increased heat generation, so-called hot spots, deteriorate the performance and reliability of nanoelectronic devices [1], while experimental characterization is restricted by limited spatial resolution in thermometry. Since local self-heating is of increasing importance for future devices, where scaling, integration of novel materials and structures tend to impede heat conduction, new methods and instrumentations are needed to study the coupling between thermal, electrical and structural properties at the level of individual operating devices.

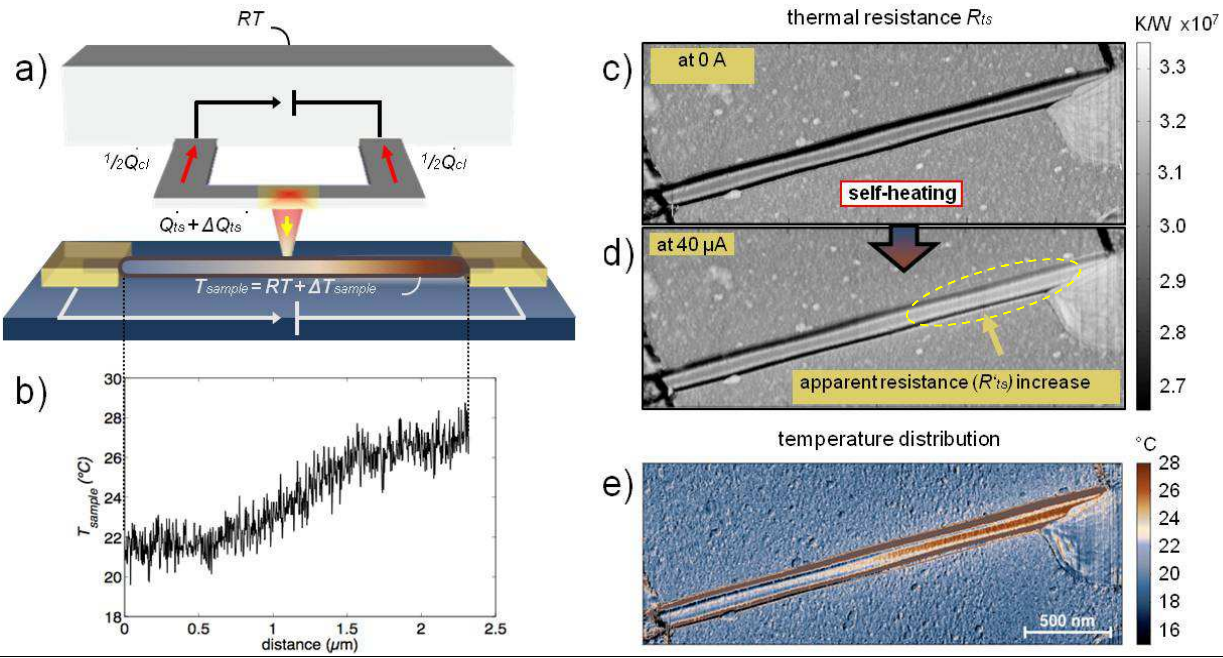

***Figure 1:* Scanning thermal microscopy for thermometry of nanoscale temperature distribution.**
a) Schematic of the experiment including cantilevered SThM tip with integrated heater/sensor and active nanowire (NW) device (InAs NW with Au contacts). b) Temperature distribution along the NW extracted from SThM data. c) Reference measurement of the position dependent thermal resistance of the tip-sample contact R_{ts} using an idle sample at RT. d) Repeated measurement with self-heated NW showing an apparent increase of R_{ts} locally along the NW. e) Extracted temperature distribution map.

With decreasing size of microelectronic devices, the thermal hot spots can reach dimensions below 10 nm. On this length scales thermometry is not yet very advanced. Scanning Thermal Microscopy (SThM) [2] appears to be an ideal method to address the challenge. By moving a sharp tip attached to a heater/sensor in contact with a device of interest, thermal signals relating to thermal conductance and temperature distribution within a sample can be inferred.

Despite recent progress using the method [3-6], however, it remains a challenge to extract quantitative data from measured SThM images on the nanoscale. One of the reasons for this is the fact that a large thermal resistance separates the sample region to be measured from the integrated heater/sensor. Sensor and sample do therefore not equilibrate. This poses several calibration challenges and systematic errors to the SThM method. In this presentation the most important systematic errors of the method are discussed and the efforts to eliminate them will be described. Application examples and measurements on nanoscale test structures will be shown.

The large thermal resistance between the SThM sensor tip and the sample is expected to increase strongly when scaling down to the nanoscale due to surface-to-volume scaling. Consider, for example, the case of an anticipated lateral resolution of 10 nm at an accuracy of ΔT_{sample} = 1 K. The thermal resistance of the contact between the contacting tip and the sample can then be dominated by the interface thermal resistance and fall in the range of $R_{ts} = 10^7 - 10^9$ K/W leading to a heat flux down to 1 nW. In contrast, the electrical leads leading to the temperature sensor within the cantilevered SThM tip have a thermal resistance R_{sensor} of typically 2 to 4 orders of magnitude smaller, leading to temperature rises in the sensor of $\Delta T_{sensor} < 1$ mK. Furthermore, R_{int} varies strongly as a function of tip position while scanning the sample surface, i.e. $R_{ts} = R_{ts}(x,y)$. Reasons for this are topography artifacts caused by a varying contact diameter between the tip and the sample surface, the variation of the local sample thermal conductivity, and the load force between tip and sample [7]. For the quantitative interpretation of the data therefore $R_{ts}(x,y)$, $\Delta T_{sensor}(x,y)$ and R_{sensor} have to be determined experimentally.

A two-pass method [5] serves to quantify these signals: The thermal resistance of the tip-sample contact R_{ts} (consisting mainly of R_{int}, and the spreading resistances in tip and sample) are determined from the heat flux from the sensor into the sample Q_{ts} and the temperature difference between the sensor temperature T_{sensor} and room temperature RT:

$$\dot{Q}_{ts} = (T_{sensor} - RT)/R_{ts} \tag{1}$$

For a sample at temperature $RT+\Delta T_{sample}$ we therefore have:

$$\dot{Q}'_{ts} = \left(T_{sensor} - \{RT + \Delta T_{sample}\}\right)/R_{ts} \tag{2}$$

The measurement process is illustrated in Fig. 1. First, we measure R_{ts} for each image pixel using an unheated sample ($R_{ts}(x,y)$) from the measured tip-sample heat flux using Eq. (1), as shown in Fig. 1c. Next, the measurement is repeated on the self-heated sample to determine a modified heat flux Q_{ts}' from which the sample temperature ΔT can be determined using Eq. (2). Self heating effects can be directly seen plotting the *apparent* thermal resistance $R_{ts} = (T_{sensor} - RT)/\dot{Q}_{ts}$, see Fig. 1d. The resulting ΔT is plotted in Fig. 1b and e.

Recently, the proposed method was developed further to reach a resolution of ΔT_{sample} in the mK-range at a lateral resolution of below 10 nm [8]. The talk will describe examples of isolated hot-spots in nanowire devices (Figure 2) and metal interconnect structures. Furthermore, effects of Peltier and Joule heating will be discussed.

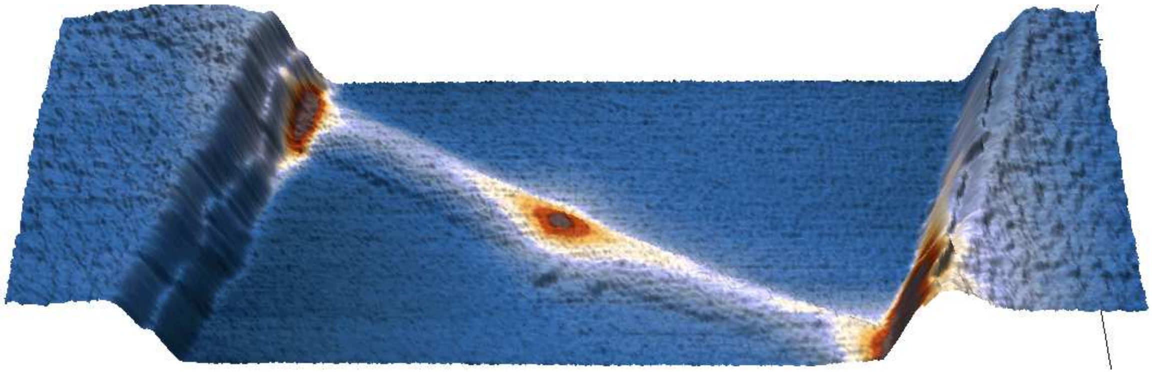

***Figure 2:* Hot spots in self-heated single vanadium oxide nanowire as measured using SThM.**
The image shows a topography image of a vanadium oxide nanowire contacted using gold electrodes and supported by a silicon nitride substrate. The image size is 2.5 x 0.8 μm² and the height of the electrodes is 40 nm. The color scale denotes the thermal signal overlayed onto the topography. A local hotspot at the center of the wire is caused by local defects, two more hot spots can be observed at the contacts to the metal electrodes.

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