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Thermal mapping of a scanning thermal microscopy tip

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ABSTRACT

Scanning thermal microscopy (SThM) is a very promising technique for local investigation of temperature and thermal properties of nanostructures with great application potential in contemporary nanoelectronics and nanotechnology. In order to increase the localization of SThM measurements, the size of probes has recently substantially decreased, which results in novel types of SThM probes manufactured with the use of modern silicon microfabrication technology. Quantitative SThM measurements with these probes need methods, which enable to assess the quality of thermal contact between the probe and the investigated surface. In this paper we propose a tip thermal mapping (TThM) procedure, which is used to estimate experimentally the distribution of power dissipated by the tip of an SThM probe. We also show that the proposed power dissipation model explains the results of active-mode SThM measurements and that the TThM procedure is reversible for a given probe and sample.

1. Introduction

Scanning thermal microscopy (SThM) is one of many scanning probe microscopy (SPM) techniques that are used for micro- and nanoscale investigations. Its idea is to add to regular atomic force microscopy (AFM) the capability of measurements of temperature and thermal properties. In general, a scanning thermal microscope is realized by adding a dedicated probe and a control module to a standard contact-mode AFM. Therefore, such a microscope is able to record a thermal image simultaneously with imaging the surface topography. First attempts to use thermal effects for SPM-based imaging date back to the late 1980s [1]. These have been followed by measurements of thermal properties in the early 1990s [2,3]. Owing to the continuous development of the technique, since the first experiments the spatial resolution of the thermal image has reached the order of tenths of nanometers [4,5]. Further progress of SThM techniques relies on novel nanoprobes, enabling more localized measurement, and on giving the means for quantitative investigation. In the presented work we show a tip thermal mapping (TThM) method, which is a step forward in the field of quantitative thermal measurement of nanostructures.

Generally, two basic SThM modes can be distinguished. The passive mode (P-SThM), usually operated as constant-current mode, enables temperature measurement based on temperature-induced changes of tip properties (e.g. resistance or electric potential). The active mode (A-SThM), sometimes controlled as a constant-temperature mode, introduces tip-induced heating of the sample and therefore enables measurement of thermal conductivity. The idea of A-SThM is to record how much heating power was needed to keep the tip temperature constant. Such data can provide even quantitative information on the thermal conductivity of the investigated sample [6].

Since the SThM technique was established, the nanoprobe has been crucial for achieving reliable thermal images. Various solutions have been proposed, including thermoresistive probes [5–11], thermocouple-based probes [12], polyimide probes [13] or fluorescent probes [14]. Regardless of the physical background of probe operation, the understanding of thermal transport between the tip and the investigated surface is an important issue. This is especially noticeable in the innovative probes [9–11]. In commercially available VITA-type SThM probes (Bruker AXS/Kelvin Nanotechnology, available also as KNT-SThM or Anasys ThermaLever probes; the acronym VITA originally stood for 'Veeco Instruments thermal analysis') the thermoresistor is placed on a silicon nitride support layer. Therefore, it is unlike the free platinum wire known from Wollaston probe, as the heat from the tip may be not dissipated to the sample uniformly in all directions (in A-SThM) or the heat from the structure may be observed differently depending on e.g. scan direction or angle (in P-SThM).

The problem of modeling the thermal contact between the probe and the surface in SThM is crucial for quantitative measurements

Abbreviations: TThM, Tip thermal mapping; SThM, Scanning thermal microscopy; P-SThM, Passive-mode scanning thermal microscopy; A-SThM, Active-mode scanning thermal microscopy; SPM, Scanning probe microscopy; AFM, Atomic force microscopy; BTR, Blind tip reconstruction; RBTR, Regularized blind tip reconstruction.

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of thermal conductivity with spatial resolution in the range of single nanometers. They were only a few works in the past in which the nature of heat transfer between the probe and the surface had been undertaken. Gomes et al. in Ref. [15] investigated the contribution of different heat transfer mechanisms in case of Wollaston probe in dc operation mode (in which dc current is flowing through the thermal tip). They stated that in air for temperatures up to 90 °C the heat transfer through water meniscus dominates the dissipated power. Above this temperature, depending on sample conductivity, solid–solid (high-conductivity sample) or solid–gas–solid (low-conductivity sample) conduction dominates. The problem of SThM calibration in order to measure sample conductivity quantitatively in dc mode is proposed by Lefevre et al. in Ref. [16]. They show that the probe cannot be treated as isothermal and propose combination of numerical analysis with SThM measurements in order to determine the area of contact surface between the probe and the sample. Furthermore, Lefevre and Voltz in [17] show that in ac mode (the thermal tip is supplied with ac current), especially in so-called 3ω mode, the sensitivity of the SThM measurements increases significantly and the results do not depend on ambient temperature. These authors also show that in this mode it is possible to determine the probe radius before the probe is brought to contact.

All these efforts usually simplify the analysis of the probe-sample contact and omit the influence of the probe shape and surface topography. But nowadays the SThM probes dimensions are much lower and the analyzed surface cannot be always treated as flat one. Also the probes are made in complex silicon-based technology, which introduces some additional uncertainties in measurements. These facts were noted by Bodzenta et al., who in Ref. [9] used the numerical modeling in order to describe VITA-like SThM probes. This methodology enables determination of influence of sample conductivity on sensitivity of the SThM measurements. Unfortunately, numerical modeling needs details of fabrication technology of the SThM probes. These details are usually unavailable for the experimenter, which limits the application of these procedures to probe manufacturers.

In our work we introduce a tip thermal mapping (TThM) method, which allows determining the map of power dissipated by an unknown probe on the basis of combined AFM and SThM measurements and advanced digital image processing procedures. We think that such a map is useful for assessment of the tip metallization quality and degradation during operating period. It may be also the first step towards deconvolution of topography influence on SThM imaging. Furthermore, the knowledge about tip thermal properties enables future metrological investigation of nanostructures; lack of methods for local high-sensitivity quantitative measurements is one of the technological barriers in nanotechnology.

The TThM method starts with regularized blind tip reconstruction (RBTR) to acquire the tip shape [18]. Then information on tip thermal energy dissipation is taken from an A-SThM scan. In this paper the TThM result is also compared with an image of the tip obtained using scanning electron microscopy (SEM).

2. Methodology

2.1. Blind tip reconstruction

The blind tip reconstruction (BTR) methods enable determination of the probe shape on the basis of an image of calibration sample with unknown geometry. It means that we do not need any information about the surface shape and dimensions (e.g. angles). By BTR methods we obtain the largest probe shape consistent with the image. If the calibration standard consists of structural elements with aspect ratios lower than the probe aspect ratio, this upper bound on the probe becomes a good approximation of the true probe shape.

In Fig. 1, using 2D simulations, we illustrate the principle of operation of the BTR methodology. The resulting AFM image is the measured surface morphologically dilated by the shape of probe reflected to its apex. Three indicated image points enable determination of shape of the probe, which scan the surface. At each point we modify probe in such a way that its center remains constant and the rest of the probe is consistent with the image. At the first step (Fig. 1, point no. 1) we assume that the probe is maximally blunt. Red line positions are rejected because in this position we need to modify the center of the estimated probe. The probe shape, in which such modification does not occur, is drawn by a solid black line. This shape becomes our upper bound on the probe shape. At the point no. 2 the procedure is repeated but the modified shape is an upper bound reconstructed at point no. 1. The final probe shape, that is the true tip shape reflected through the apex, is determined at point no. 3. In the presented example the true probe shape is determined because of the presence of steep edges at points no. 2 and 3.

The basic drawback of BTR methods is their sensitivity to noise. Probe shape blindly reconstructed from the noisy AFM image is unphysically sharp. In Fig. 2 we present a simulated example of the noise influence on the blindly reconstructed probe shape.

In the most popular BTR technique introduced by Villarubia [19] the regularization mechanism is proposed.

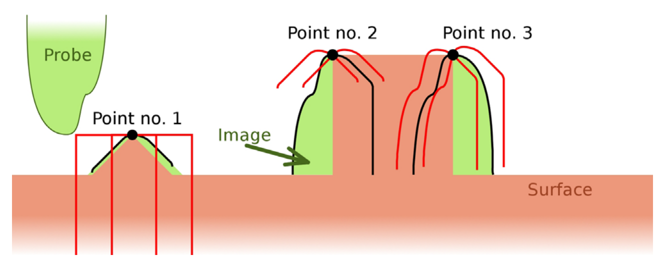

Fig. 1. Illustration of the blind probe reconstruction method. Three indicated image points enable determination of the shape of the probe, which scanned the surface. At each point, by the red line we indicate possible probe positions that may produce the image. However, the apices of these probes are not placed at their centers. By black lines we indicate probe positions that may produce the image. In case of these probe shapes the apices are placed at the centers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

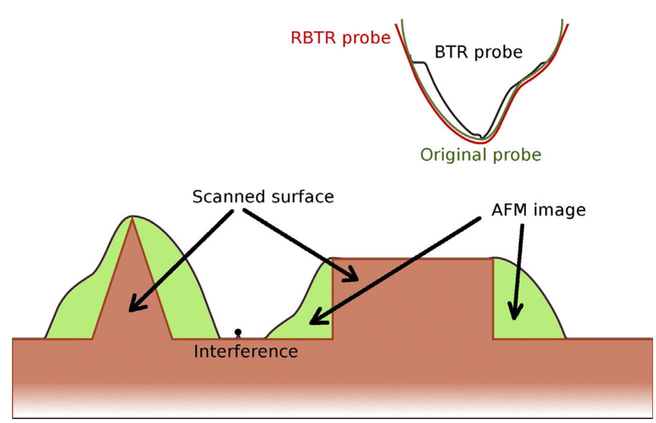

Fig. 2. Illustration of noise influence on BTR probe. In the presented case, without the illustrated interference BTR would estimate the real shape of a probe used in scanning process. Unfortunately, even such a small and single interference causes that the reconstructed probe is much sharper than the real one. This problem is avoided in case of RBTR procedure.