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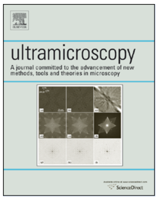

Scanning thermal microscopy with heat conductive nanowire probes

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ABSTRACT

Scanning thermal microscopy (SThM), which enables measurement of thermal transport and temperature distribution in devices and materials with nanoscale resolution is rapidly becoming a key approach in resolving heat dissipation problems in modern processors and assisting development of new thermoelectric materials. In SThM, the self-heating thermal sensor contacts the sample allowing studying of the temperature distribution and heat transport in nanoscaled materials and devices. The main factors that limit the resolution and sensitivities of SThM measurements are the low efficiency of thermal coupling and the lateral dimensions of the probed area of the surface studied. The thermal conductivity of the sample plays a key role in the sensitivity of SThM measurements. During the SThM measurements of the areas with higher thermal conductivity the heat flux via SThM probe is increased compared to the areas with lower thermal conductivity. For optimal SThM measurements of interfaces between low and high thermal conductivity materials, well defined nanoscale probes with high thermal conductivity at the probe apex are required to achieve a higher quality of the probe-sample thermal contact while preserving the lateral resolution of the system.

In this paper, we consider a SThM approach that can help address these complex problems by using high thermal conductivity nanowires (NW) attached to a tip apex.

We propose analytical models of such NW-SThM probes and analyse the influence of the contact resistance between the SThM probe and the sample studied. The latter becomes particularly important when both tip and sample surface have high thermal conductivities. These models were complemented by finite element analysis simulations and experimental tests using prototype probe where a multiwall carbon nanotube (MWCNT) is exploited as an excellent example of a high thermal conductivity NW. These results elucidate critical relationships between the performance of the SThM probe on one hand and thermal conductivity, geometry of the probe and its components on the other. As such, they provide a pathway for optimizing current SThM for nanothermal studies of high thermal conductivity materials. Comparison between experimental and modeling results allows us to provide direct estimates of the contact thermal resistances for various interfaces such as MWCNT-Al ($5\times10^{-9}\pm1\times10^{-9}\ \mathrm{K\,m^2\,W^{-1}}$), Si_3N_4–Al ($6\times10^{-8}\pm2.5\times10^{-8}\ \mathrm{K\,m^2\,W^{-1}}$) and Si_3N_4 – graphene ($\sim10^{-8}\ \mathrm{K\,m^2\,W^{-1}}$). It was also demonstrated that the contact between the MWCNT probe and Al is relatively perfect, with a minimal contact resistance. In contrast, the thermal resistance between a standard Si_3N_4 SThM probe and Al is an order of magnitude higher than reported in the literature, suggesting that the contact between these materials may have a multi-asperity nature that can significantly degrade the contact resistance.

1. Introduction

Modern materials science and technology is increasingly devoted to the control of matter on the nanoscale, with local thermal properties playing a major role in the diverse materials used in renewable energy generation (thermoelectrics and photovoltaics), structural composites and in optical and electronic devices [1–6]. In semiconductor processors, the inability to dissipate increasing power density leads to the failure of Moore's law due to nanoscale thermal management problems [7–9]. Tools able to perform thermal measurements of solid state materials on the nanoscale are needed to address these problems. Unfortunately, most thermal measurement

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systems are based on optical methods, such as IR thermal emission, Raman spectroscopy or photoreflectance with the spatial resolution limited in the best case to 500 nm or greater [10–12]. A promising technique for nanoscale thermal measurements is Scanning Thermal Microscopy (SThM) [13–19]. While showing good performance in studies of polymeric and organic materials, SThM has a limited ability to study high thermal conductivity materials such as those frequently used in the semiconductor industry, e.g., heatsinks in integrating circuits and thermoelectric assemblies or optical devices. The main limiting factors for conventional SThM are briefly summarized: (i) SThM spatial resolution, which is in the range of a few tens of nanometers, remains well below most other scanning probe microscopy (SPM) approaches: (ii) SThM has low sensitivity to thermal properties of materials of high thermal conductance such as metals and single crystal semiconductors that are indispensable for the semiconductor industry and nanotechnology; and (iii) finally the performance of SThM is significantly affected by the unstable and weak thermal contact between the heat sensor and the specimen studied.

One of the possible solutions proposed elsewhere [4,5,20,21] suggests to use a high thermal conductivity and nanometer scale cross-section probe at the apex of the tip (e.g. nanowire (NW) or multiwall carbon nanotube (MWCNT), a particular example of NW) to act as a nanometer scale thermal link between the sensor and the sample [21,22]. The first experimental tests [5,22] showed the high potential of such an approach. This paper focuses on the understanding of the physical principles underlying the operating envelope of such high performance SThM probes. It also correlates the geometry of the probe and the characteristics of the materials used. An analytical thermal model was developed considering all probe components to define overall SThM sensitivity and spatial resolution. The validity of the model was tested by comparing finite elements analysis to experimental measurements. This allowed us to propose the optimal geometry and materials for such a high performance probe including semiconductor and MWCNT based thermal nanowires that may add new functionalities to SThM measurements. The thermal sensitivity of the NW-probe was compared with the experimental results obtained using MWCNT-probe. We then analyse future directions to optimize the performance of such SThM probes in air and vacuum environments. For simplicity, the term “NW” is used throughout the paper for both semiconducting and MWCNT nanowires.

2. Theory and simulation

2.1. Analytical model of the SThM probe

Fig. 1 shows a scanning electron microscope (SEM) image of the widely used SThM probes (Kelvin Nanotechnologies) [18,19] with a Si_3N_4 cantilever and Pd/NiCr heater. This SThM cantilever has a Si_3N_4 cantilever base with Au pads, that are highly conductive both electrically and thermally [23] (Fig. 1a). The high resistance Pd/NiCr heating resistor acts as a thermal sensor and is positioned on the triangular part of the cantilever (Fig. 1b) and the probe apex zone that is either in direct thermal contact with the sample or via a NW attached [4,22] (Fig. 1c).

It was demonstrated elsewhere [4,6,24–26] that the thermal properties of the tip apex have a major impact on the performance of the SThM probe. Therefore, this study focuses on the apex of the SThM probe (dashed square in the Fig. 1b and c) and the contact of the probe with the sample studied. The equivalent thermal resistance of the SThM probe is schematically presented in Fig. 2, in line with previously reported models [4,23].

Here R_c is the thermal resistance of the cantilever base, R_{mfull} is the thermal resistance of the heat flow to the media surrounding the cantilever (excluding the flow from the apex of the thermal sensor), Q_h the heating power generated by the probe heater, R_h is the thermal resistance for heat flow through the thermal sensor, R_t is the additional thermal resistance of the NW, R_{t-s} is the thermal resistance of the interface (contact resistance) between NW and

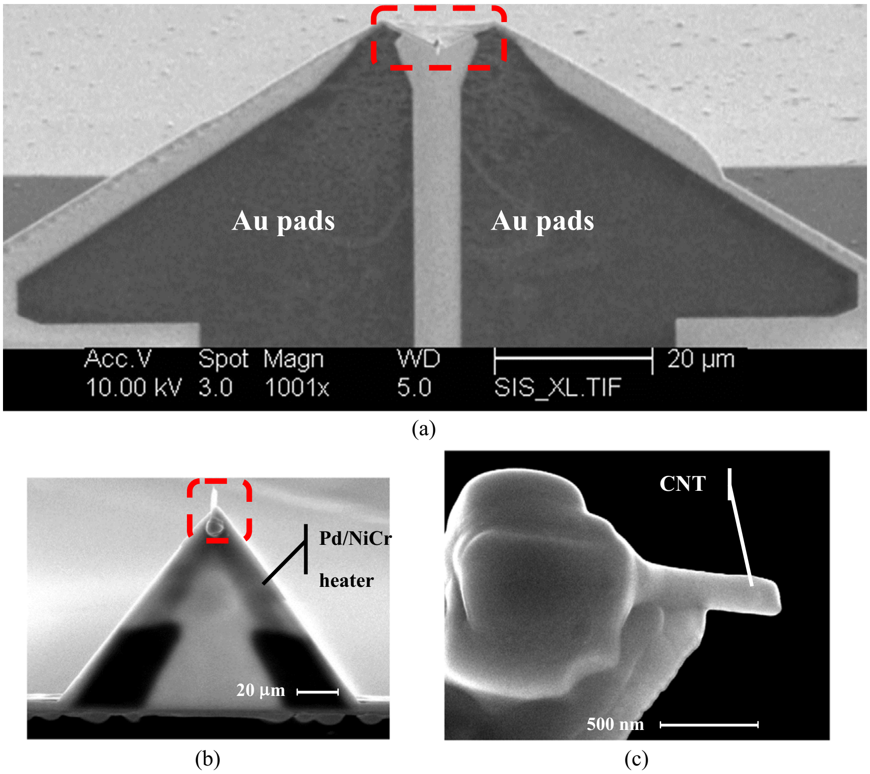

Fig. 1. SEM image of the SThM cantilever, (a) SThM cantilever base with Au pads, (b) high resistance Pd/NiCr heating resistor that also acts as a thermal sensor that is positioned on the triangular part of the cantilever (scale 2 µm), and (c) attached NW (scale 500 nm).