Scanning Thermal Microscopy – current applications and perspectives

Bodzenta J[(1)*], Kaźmierczak-Bałata A[(1)]

(1) Institute of Physics, Silesian University of Technology, Gliwice, Poland

*Corresponding author's email: jerzy.bodzenta@polsl.pl

Background – In the last few decades nanotechnology is of growing importance in many areas of science and technology. A production of structures with the length scale of several nanometres is a standard in electronic industry. Nowadays technology allows fabrication of low-dimensional structures, e.g., quantum dots, nanowires, and 2D materials like graphene, silicene, etc. Transport phenomena in such structures cannot be described by classical laws, new approaches are necessary. In a case of thermal measurements, the scanning thermal microscopy (SThM) is a method with a great potential.

SThM – principle, instrumentation, operation modes – The SThM was developed by Williams and Wickramasinghe in 1986 [1, 2]. Currently used microscopes utilize working principle described by Majumdar *et al.* in 1993 [3]. The idea was to combine topographical imaging by atomic force microscope (AFM) with thermal imaging. For this purpose, special thermal probes (TPs), with the temperature sensor placed near the probe apex, are used. The SThM operates in two basic modes: the temperature contrast mode (TCM) and the conductance contrast mode (CCM). The TCM is a passive mode in which the TP measures the local temperature of sample surface. The CCM is an active mode. The TP is heated, and its temperature rise θ depends on dissipated power P, and the thermal conductance G_{th} for the heat flow J from the TP to the surroundings

$$\theta = \frac{P}{G_{\mathrm{th}}} \qquad \text{Eqn. 1}$$

In a steady-state P is equal to J. A certain part of J flows to the sample and depends on the sample thermal conductivity k. Therefore, the sensor temperature also depends on k. As a result, the SThM can be used for determination of local thermal conductivity of sample.

For quantitative measurement the TP must be calibrated. A calibration in TCM mode is relatively simple. The main problem is that the temperature sensor is not in thermal equilibrium with the sample. Therefore, the probe temperature differs from the one of sample. A few measuring techniques were proposed to solve this problem [4-6]. In the case of CCM mode the situation is more complex. The thermal transport from the TP to the sample is influenced by many factors. The heat flows through the TP-sample contact but also through its surroundings (the air, the water meniscus). Moreover, the energy is also transferred by thermal radiation. Some mechanisms are excluded in the vacuum SThM. The heat transport through the contact depends on: the sample surface roughness, the constriction resistance, and the boundary resistance. Detailed analysis of the problem can be found in review papers [7, 8].

Thermal probes – The probe is a key element of each scanning microscope. It defines the physical quantity, which can be measured, and spatial resolution of measurements. As it was mentioned above, probes used for SThM must provide temperature measurement. Temperature sensors utilize dependence of any physical quantity on temperature. In practice, TPs must meet a few conditions. They should be compatible with a standard scanning microscope. The probe signal should be easily detected and processed. Probes should have repeatable parameters.

The most popular are resistive TPs, which utilize a dependence of electrical resistance on the temperature. Comprehensive description of commercially available resistive TPs can be found in Ref. [9]. Thermoelectric TPs, with a thermocouple junction on the tip, are also used quite often.

Theory and modelling – The correct interpretation of the SThM measurement results requires an understanding of the thermal transport phenomena occurring in the measuring system. Because of complex geometry of the TP-sample system, exact analytical description of the thermal transport in the system is not possible. Simplified analytical models based on the thermal fin equation with a Joule dissipation term were used [10]. The main advantages of the model are that it allows determination of the temperature distribution along the TP, and its frequency characteristics. However, the thermal fin model corresponds only to the geometry of Wollaston probe. Application of fin model to describe other probes is difficult to justify.

A well-known tool for the heat transfer modelling is the quadrupole method. The method is based on electro-thermal analogies. It was successfully used for analysis of frequency characteristics and sensitivity to G_{th} in SThM measurements with the resistive TP driven by a sum of dc and ac electric currents [11]. The electro-thermal analogies are also used for modelling the TP-sample heat exchange [7, 8].

The SThM measurements are also modelled numerically. The most popular method is the finite element method. This approach allowed analysis of complex geometries and can be use from macroscale to nanoscale. In the case of SThM numerical models, the method allowed either the investigation of radiative thermal transport in nanoscale [12] or processes in the whole TP-sample system [9].

Examples of SThM measurements – Since its development, the SThM found many applications in research. It was used for *k* measurements of thin films [13] and nanowires [14]. It allowed investigation of nanoscale hot spots [6], thermoelectric effects in graphene nanoconstrictions [15], and temperature mapping of operating nanoscale devices [16]. These are just a few examples.

Conclusions – The scanning thermal microscopy is the only method allowing thermal measurements with spatial resolution in the nanometre range. However, it has number of limitations. The thermal conductance for the heat flux to the sample depends on sample roughness; and is also influenced by sample topography. Therefore, samples must be smooth and flat for quantitative measurements. Moreover, the SThM signal is influenced by ambient conditions, e.g., humidity. To exclude environmental influences measurements are often carried out in a vacuum. Quite complex theoretical model of measurement causes that the measurement methodology is not well established. Moreover, the sensitivity of SThM signal to *k* is low. All these difficulties cause that at present the use of the SThM is limited to scientific research. Possible development can be probably achieved by using new TPs, whose construction will be like those used in classical AFM.

Despite all these limitations, it should be underlined that SThM opens a window to observe thermal transport in the nanoscale, where new phenomena can be observed.

References

[1] C.C. Williams, H.K. Wickramasinghe, Scanning thermal profiler, Appl. Phys. Lett. 49 (1986) 1587-1589. https://doi.org/10.1063/1.97288.

[2] C.C. Williams, H.K. Wickramasinghe, High resolution thermal microscopy, 1986 IEEE Ultrasonics Symposium Proceedings (IEEE, New York, 1986), pp. 393-397. https://doi.org/10.1109/ultsym.1986.198771.

[3] A. Majumdar, J.P. Carrejo, J. Lai, Thermal imaging using the atomic force microscope, Appl. Phys. Lett. 62 (1993) 2501-2503, https://doi.org/10.1063/1.109335.

[4] K. Kim, J. Chung, J. Won, O. Kwon, J.S. Lee, S.H. Park, Y.K. Choi, Quantitative scanning thermal microscopy using double scan technique, Appl. Phys. Lett. 93 (2008) 203115. https://doi.org/10.1063/1.3033545.

[5] J. Chung, K. Kim, G. Hwang, O. Kwon, S. Jung, J. Lee, J.W. Lee, G.T. Kim, Quantitative temperature measurement of an electrically heated carbon nanotube using the null-point method, Rev. Sci. Instrum. 81 (2010) 114901. https://doi.org/10.1063/1.3499504.

[6] F. Menges, H. Riel, A. Stemmer, B. Gotsmann, Quantitative thermometry of nanoscale hot spots, Nano Lett. 12 (2012) 596-601. https://doi.org/10.1021/nl203169t.

[7] S. Gomès, A. Assy, P.-O. Chapuis, Scanning thermal microscopy: A review, Phys. Status Solidi A 212 (2015) 477-494. https://doi.org/10.1002/pssa.201400360.

[8] Y. Zhang, W. Zhu, F. Hui, M. Lanza, T. Borca-Tasciuc, M. Muñoz Rojo, A review on principles and applications of scanning thermal microscopy (SThM), Adv. Func. Mater. 29 (2019) 1900892. https://doi.org/10.1002/adfm.201900892.

[9] Y. Zhang, W. Zhu, T. Borca-Tasciuc, Sensitivity and spatial resolution for thermal conductivity measurements using noncontact scanning thermal microscopy with thermoresistive probes under ambient conditions, Oxford Open Mater. Sci. 1 (2021) itab011. https://doi.org/10.1093/oxfmat/itab011.

[10] S. Lefèvre, S. Volz, 3ω-scanning thermal microscope, Rev. Sci. Instrum. 76 (2005) 033701. https://doi.org/10.1063/1.1857151.

[11] J. Bodzenta, M. Chirtoc, J. Juszczyk, Reduced thermal quadrupole heat transport modeling in harmonic and transient regime scanning thermal microscopy using nanofabricated thermal probes, J. Appl. Phys. 116 (2014) 054501. https://doi.org/10.1063/1.4891872.

[12] K.L. Nguyen, O. Merchiers, P.-O. Chapuis, Near-field radiative heat transfer in scanning thermal microscopy computed with the boundary element method, J. Quant. Spectrosc. Radiat. Transf. 202 (2017) 154-167 https://doi.org/10.1016/j.jqsrt.2017.07.021.

[13] J. Juszczyk, A. Kaźmierczak-Bałata, P. Firek, J. Bodzenta, Measuring thermal conductivity of thin films by Scanning Thermal Microscopy combined with thermal spreading resistance analysis, Ultramicroscopy 175 (2017) 81-86. https://doi.org/10.1016/j.ultramic.2017.01.012.

[14] A. El Sachat, J.S. Reparaz, J. Spiece, M.I. Alonso A.R. Goñi, M Garriga, P.O. Vaccaro, M.R. Wagner, O.V. Kolosov, C.M. Sotomayor Torres, F. Alzina, Thermal transport in epitaxial $Si_{1-x}Ge_x$ alloy nanowires with varying composition and morphology, Nanotechnology 28 (2017) 505704. https://doi.org/10.1088/1361-6528/aa9497.

[15] A. Harzheim, J. Spiece, C. Evangeli, E. McCann, V. Falko, Y. Sheng, J.H. Warner, G.A.D. Briggs, J.A. Mol, P. Gehring, O. V. Kolosov, Geometrically Enhanced Thermoelectric Effects in Graphene Nanoconstrictions, Nano Lett. 18 (2018) 7719-7725. https://doi.org/10.1021/acs.nanolett.8b03406.

[16] F. Menges, P. Mensch, H. Schmid, H. Riel, A. Stemmer, B. Gotsmann, Temperature mapping of operating nanoscale devices by scanning probe thermometry, Nat. Commun. 7 (2016) 1-6. https://doi.org/10.1038/ncomms10874.