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# ADP013201

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## This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology International Symposium [9th], St. Petersburg, Russia, June 18-22, 2001 Proceedings

9th Int. Symp. “Nanostructures: Physics and Technology”
St Petersburg, Russia, June 18–22, 2001

# Scanning Joule expansion microscopy as a tool for studying local heating phenomena

*M. Cannaerts*†, R. J. M. Vullers‡ and Chris Van Haesendonck†
† Laboratorium voor Vaste-Stoffysica en Magnetisme, Katholieke Universiteit
Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium
‡ Philips Research Laboratories, Prof. Holstlaan 4,
NL-5656 AA Eindhoven, The Netherlands

**Abstract.** Scanning Joule expansion microscopy (SJEM) is a powerful technique enabling the generation of temperature maps of nanostructured samples [1]. It operates by examining in detail the thermal expansion of a current-carrying structure with an atomic force microscope (AFM). The thermal expansion varies proportional to the temperature, making it possible to simultaneously generate topographical maps as well as thermal maps of samples. The lateral resolution of the SJEM technique (estimated to be 20 nm or better) is considerably better than that of other comparable techniques (e.g. scanning thermal microscopy, with a typical resolution of 100 nm). Previously we implemented and optimized a SJEM in an existing AFM system [2]. Using the SJEM technique it is possible to identify ‘hot spots’, and to examine in detail the temperature profile in nanostructured materials. Here, we investigate the reliability of this technique for microelectronics related applications.

## Introduction

The ever decreasing dimensions of microelectronic structures has made it necessary for engineers and physicists to look for new and better characterization tools. Scanning probe microscopes have proven to be valuable and versatile tools for quality control of samples with submicrometer dimensions. Recently, new lithography techniques (based on extreme ultraviolet light with a wavelength of 13.4 nm) have been announced, making it possible to fabricate 30 nm sized transistors. Chips generated with this technique could consist of 400 million transistors, making 10 GHz operating speeds attainable in the near future [3]. One of the major issues linked to this continuing downscaling of features, is the problem of local heat generation and dissipation.

An atomic force microscope (AFM) can be adapted to map local variations of the temperature. This technique is referred to as ‘scanning thermal microscopy’ (SThM), and relies on the use of a microfabricated thermocouple or a small resistor as the local probe [4, 5]. The SThM technique makes it possible to generate temperature maps of a sample surface or plots of the thermal conductivity. While the resolution of SThM is much better than that of other techniques (for example infrared imaging), the resolution is still limited to 100 nm for typical commercially available setups. A 25 nm spatial resolution was obtained using thin film technology coupled with electron beam lithography [6]. This seems to be the realistic limit for the SThM technique under ambient conditions because of the nature of the tip-sample thermal contact. For more detailed information on SThM we refer the reader to a recent review article [7].

## 1. Experimental setup

An alternative powerful and versatile technique to map local temperature variations of surfaces was recently presented [1]. An atomic force microscope, operating with a silicon cantilever, scans the surface of a current-carrying structure. By examining in detail the thermal expansion (due to Joule heating) of the structure at a given point (which is proportional to the temperature at that point), it is possible to infer the local temperature. This technique is called 'scanning Joule expansion microscopy' (SJEM). The signal to noise level is considerably improved by working with ac currents and a lock-in detection technique. The details of our experimental setup can be found elsewhere [2].

The advantage of the SJEM technique is that no complicated miniature thermocouple fabrication is required. Another advantage is the nature of the temperature detection: SThM operates because of heat extending into the microfabricated thermocouple. Therefore, the nature of the thermal contact between tip and sample strongly affects the resolution and the interpretation of data. On the other hand, SJEM infers the temperature from the thermal expansion of the sample. In principle, this implies a resolution comparable to that of regular AFM. The disadvantage is that only conducting structures can be thermally examined with the SJEM technique.

Our SJEM is based on a commercially available AFM setup (Park Scientific Instruments M5 autoprobe), using commercial cantilevers (type PSI *Ultralever*, with a spring constant of typically 1 to 10 N/m). Measurements were performed in the contact mode, with setpoint forces of typically 50 nN. Using the relatively stiff cantilevers in the contact mode minimizes the contribution of electrostatic forces to the expansion signal [2].

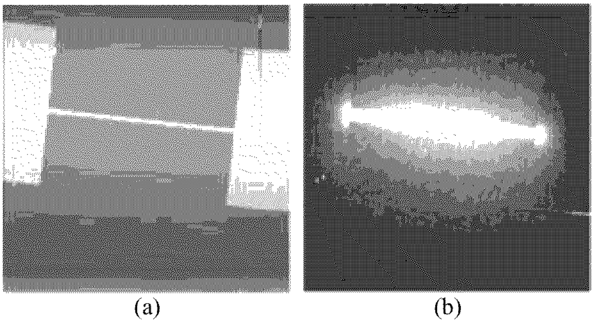
(a) (b)

**Fig. 1.** (a) Topographical AFM image of a 37 nm thick gold line on an oxidized silicon surface (length 52 micron, width 700 nm). (b) Thermal expansion (i.e. temperature map) of the line obtained with an alternating current with an amplitude of 21 mA and a frequency of 20 kHz. Black regions in the expansion map correspond to regions with a small expansion amplitude (lower temperatures), white regions have a higher expansion signal (higher temperatures).

## 2. Heat distribution in narrow gold lines

Using electron beam lithography combined with lift-off techniques, narrow gold lines were fabricated on oxidized silicon wafers. Figure 1(a) shows a typical topographical AFM picture of a gold structure. An alternating current of 21 mA at 20 kHz causes a thermal expansion of the gold line at 40 kHz, which is at too high a frequency for the AFM feedback to react. Therefore, the error signal will contain this high frequency component, which can be measured with a lock-in amplifier (Stanford Research, SR830). The dc output of the

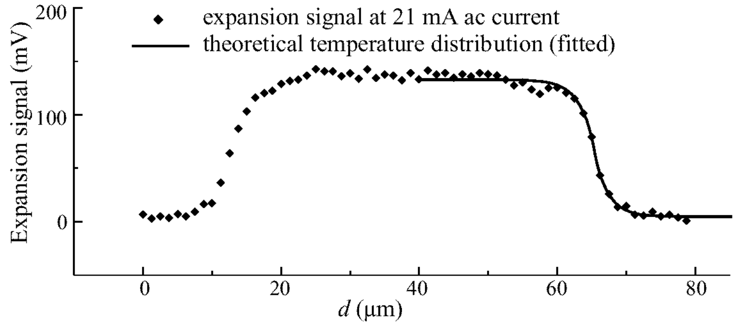

**Fig. 2.** Experimental expansion signal measured along the gold wire, which has been fitted to the theoretical temperature distribution in the wire.

lock-in amplifier gives the oscillation amplitude of the thermal expansion, and can be plotted simultaneously with the sample topography. This expansion map is visible in Fig. 1(b).

In order to prove that the measured expansion signal varies indeed proportional to temperature (and is not, e.g., strongly influenced by electrostatic force interactions between the cantilever and the sample), the measured expansion profile has been compared to the theoretical temperature profile in a small gold line (for more details, see reference [2]). Figure 2 shows the measured expansion signal which has been fitted with the theoretical temperature profile in the gold line.

## 3. Applications of SJEM

We have applied our SJEM technique to identify the 'hot spots' in copper coils. These copper coils are to be used for future magneto-optical recording systems, featuring laser-pulsed magnetic field modulation [8]. The studied copper coil is embedded in an oxide layer, and has an inner diameter of 90 $\mu$m.

Figure 3(a) shows an optical micrograph of a copper coil. Within the region marked by a square, an expansion map was generated. The three-dimensional expansion map is shown in Fig. 3(b).

Since the material in which the copper coil is embedded also expands, it is difficult to quantitatively compare the temperature on top of the copper wires to the temperature at the center of the coil. In the near future, we will try to link the expansion maps of the coils to thermal maps generated with infrared imaging techniques in order to perform a quantitative

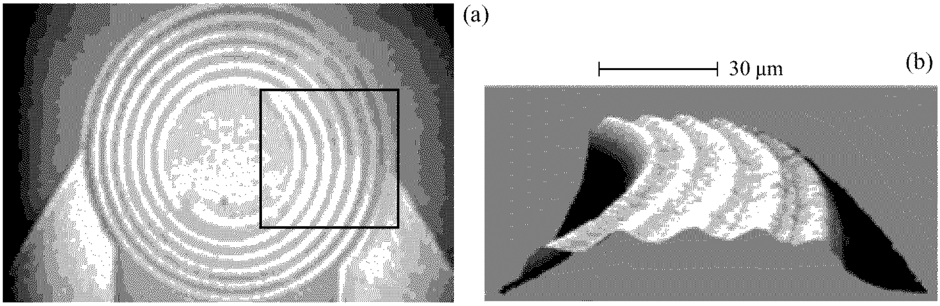

**Fig. 3.** (a) Light microscopy picture of the copper coil. (b) Thermal expansion map for the square area indicated in (a).

temperature calibration, and to check in more detail the applicability of SJEM as a quick thermal characterization tool.

*Acknowledgements*

The authors would like to thank Dieter Buntinx for sample preparation. This work has been supported by the Fund for Scientific Research Flanders (FWO) as well as by the Flemish Concerted Action (GOA) and the Belgian Inter-University Attraction Poles (IUAP) research programs.

## References

[1] J. Varesi and A. Majumdar, *Appl. Phys. Lett.* **72** 37 (1998).
[2] M. Cannaerts, G. Rens, A. Volodin and C. Van Haesendonck, *Appl. Surf. Sci.* **157** 308 (2000).
[3] http://www.newscientist.com.
[4] M. Nonnenmacher and H. K. Wickramasinghe, *Appl. Phys. Lett.* **61** 168 (1992).
[5] A. Majumdar, J. P. Carrejo and J. Lai, *Apl. Phys. Lett.* **62** 2501 (1993).
[6] K. Luo, Z. Shi, J. Varesi and A. Majumdar, *J. Vac. Sci. Technol. B* **15** 349 (1997).
[7] A. Majumdar, *Annu. Rev. Mater. Sci.* **29** 505 (1999).
[8] F. C. Penning, H. W. Van Kesteren, M. A. H. Van der Aa, Y. V. Martynov and R. J. M. Vullers, *accepted for publication in Jap. J. Appl. Phys., vol. 40* (2001).