Microelectronic Engineering 154 (2016) 12–16

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Temperature distribution in Scanning Thermal Microscopy tip investigated with micro-Raman spectroscopy☆

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ARTICLE INFO

Article history:
Received 8 October 2015
Received in revised form 2 January 2016
Accepted 15 January 2016
Available online 18 January 2016

Keywords:
Scanning Thermal Microscopy
Raman scattering
Temperature

ABSTRACT

In this work analysis of thermal behavior of piezoresistive silicon Scanning Thermal Microscopy cantilever with integrated resistive metal tip is presented. In order to determine the temperature distribution of the tip in the case of present power supply micro-Raman spectroscopy was used. Two different excitation wavelengths, in particular from visible and ultraviolet spectral ranges, were applied. The application of different excitation wavelengths results in significantly different penetration depth of the light into the silicon. As a result the information from different depths of the material is detected. The results obtained from micro-Raman spectroscopy can be summarized in two points. First: the increase of the temperature is observed only in the vicinity of conducting tracks. This increase is of the order of 10 K. Second: there is no large increase of the temperature in the thin layer of silicon substrate in the vicinity of silicon/silicon dioxide interface. Measured temperature distribution is compared with theoretical simulation calculated with Finite-Element Method and data obtained from thermal imaging. Calculated thermal effect can be summarized as follows: the temperature increases by 11 K for conducting track, and by 9 K for silicon in the vicinity of the track above the temperature of the environment. The increase of the temperature of the cantilever obtained from thermal imaging is equal to about 12 K.

1. Introduction

Scanning Thermal Microscopy (SThM) is one of the Scanning Probe Microscopy (SPM) techniques for nanoscale analysis of the surface [1]. In this technique, spring beam with integrated thermally active nanotip enables combined localized sample thermal analysis and high resolution topography investigations. In the passive mode of SThM, the micro-probe acts as a micro-thermometer, which when brought into contact with the sample measures its temperature. In the active mode of SThM, the thermal micro-probe is used as a local source of heat, which is dissipated in the investigated specimen. In this mode the thermal resistance between the micro-probe and the sample can be analyzed and local values of thermal diffusivity and thermal conductivity can be estimated [2]. However, in order to perform quantitative thermal measurements with SThM, the thermal properties of the micro-probe like: tip temperature, thermal resistance of the tip/cantilever have to be determined first.

One of the applications of micro-Raman spectroscopy is the investigation of spatial distribution of material properties. The experimental technique was widely used for investigation of mechanical stress generated in semiconductor substrate caused by manufacturing of Metal-Oxide-Semiconductor (MOS) structures [3,4]. The other application of Raman microscopy is the investigation of thermal effect in electronic devices, for example in Heterojunction Field-Effect Transistors (HFET) [5]. Micro-Raman spectroscopy makes possible the investigation of the temperature distribution crosswise [6,7] and along optical axis [8].

Design, manufacturing technology and applications of the nanotip under study were already presented in literature [9]. The fabrication process and the properties the tip important in the case of temperature measurements were discussed in detail [9]. Also the electronic set-up necessary to control the cantilever was presented [9]. The example of the temperature distribution measured with cantilever was also shown in order to present the applicability of the tip.

This work focuses the attention on the thermal properties of the tip itself. In particular: spatial distribution of the temperature in the case of active power supply is investigated. The temperature distribution in the tip in the case of active power supply is of key importance if the cantilever works in active mode. Due to small dimension of the tip micro-Raman spectroscopy is used for investigation of the temperature distribution. Application of two different excitation wavelengths is used in order to characterize “depth” of thermal effect in the developed tip. The other problem discussed in this paper is related to modeling of thermal properties of electronic devices in the microscale. The problem is not trivial, because thermal properties of different materials are usually

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☆ This paper was presented at MicroTherm 2015 and SENM Duoconference.

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http://dx.doi.org/10.1016/j.mee.2016.01.014
0167-9317/

reported for macroscale. The comparison of experimental results obtained for microtip with theoretical calculations allowed us to validate mathematical model used to predict of the thermal behavior of the microtip.

2. Experimental

2.1. Samples

Micro-Raman spectrometer MonoVista 2750i (details see Section 2.2 Raman apparatus) was used to analyze temperature distribution on the tip of Scanning Thermal Microscopy cantilever operating in active mode. In this mode tip's temperature is elevated above room temperature and the heat flux from the tip to the scanned surface is linked with local thermal conductivity of the sample. Therefore the temperature of the tip is the crucial parameter of the probe. The piezoresistive silicon Scanning Thermal Microscopy cantilever is equipped with platinum (1 μm wide, 100 nm thick) resistive microtip (placed on 100 nm thick SiO_2) located at the very end of the probe shown in Fig. 1.a. Application of 3-omega measurement approach allows for simultaneous local heating and measurement of sample-tip interface temperature [10]. Thus, the active SThM is particularly attractive for thermal conductivity/diffusivity mapping at the nanoscale. However, in order to perform quantitative thermal measurements analysis of thermal behavior of the tip is crucial. The information about dependence of tip temperature on power dissipated is of key importance for two reasons. It supports SThM cantilever design process as well as modeling activities for extraction of local thermal parameters of the investigated surface.

In this paper we describe micro-Raman measurements used for investigation of the temperature distribution in cantilever. The detailed description of manufacturing process of the cantilever was described in previous paper [9].

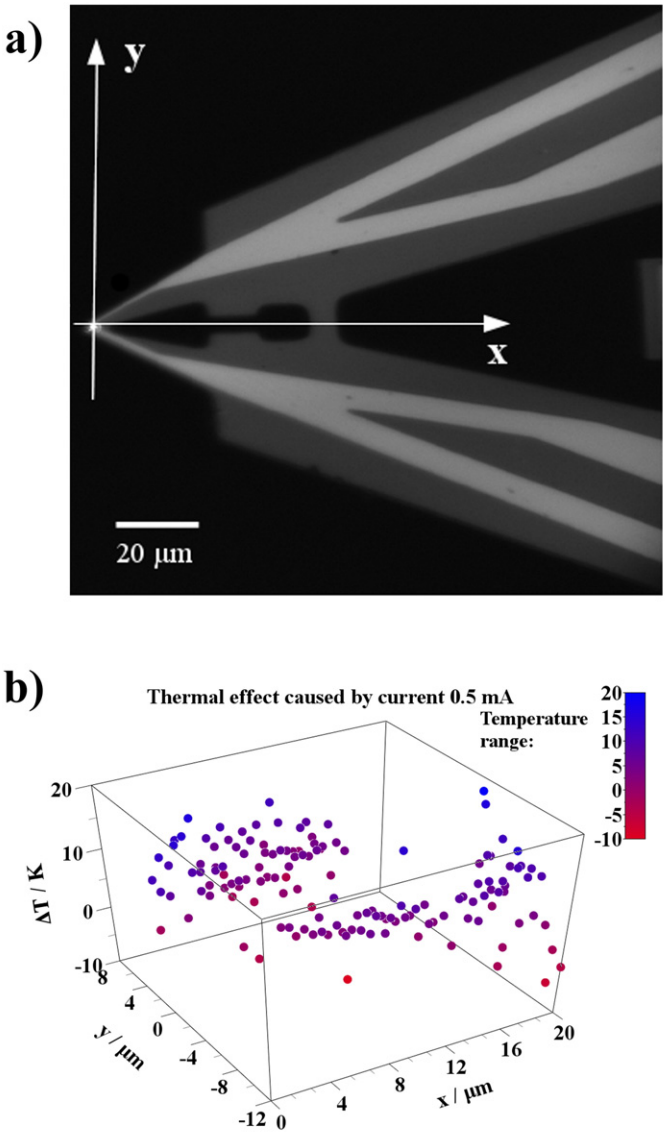

Fig. 1. Thermal effect calculation from shift of one-phonon Si Raman line measured in visible spectral range (excitation wavelength 488 nm). Part a) presents image from microscope, part b) — calculated temperature change caused by current equal to 500 μA. x and y represent coordinates of laser focus position. As (0,0) point the nook of cantilever was chosen. The legend shows the range of the ΔT presented in panel b).

2.2. Raman apparatus

Raman spectra were measured with micro-Raman spectrometer MonoVista 2750i (Spectroscopy & Imaging GmbH, Germany).

Microscopy part of the spectrometer is based on fluorescence microscope type BX-51 (Olympus, Japan). The microscope is equipped with several objectives which enable measurements in visible (VIS) and deep-ultraviolet (deep-UV) spectral ranges. In order to avoid the contact of microscope objective with the sample two long working distance objectives were used. In the case of measurements performed in visible spectral range the objective UPLFLN20X (Olympus, Japan) was applied. Measurements performed for deep-ultraviolet excitation were done with application of reflecting objective type 5004–000.X36 (Davin Optronics, UK). Both objectives have working distance equal to several millimeters what prevents the destruction of electronic connections in studied device. Images from microscope are recorded with imaging camera TM 2040 GE (JAI, Japan). Motorized stage type Tango 3 (Märzhauser GmbH, Germany) makes possible few types of spatially resolved measurements.

Spectroscopy part of the set-up is based on imaging spectrograph SpectraPro 2750i (Princeton Instruments USA) equipped with two liquid nitrogen cooled spectroscopy CCD cameras. In the case of deep-ultraviolet excitation the camera LN/2048 × 512B/IUVAR with maximum efficiency in UV spectral range was used. In the case of excitation in visible spectral range the camera LN/100B Excelon was applied. Both cameras belong to Spec-10 System (Princeton Instruments USA). The spectrograph has three diffraction gratings:

- two of them (1800 grooves/mm and 2400 grooves/mm) are blazed in VIS spectral range;
- one grating (3600 grooves/mm) is blazed in UV.

Large focal length of the spectrograph (750 mm) allows maximizing spectral resolution combined with single pass of the radiation through the spectrograph. To get the best available spectral resolution in VIS spectral range grating with 2400 grooves/mm was used.

As excitation sources two continuous work (CW) lasers were used. Raman scattering in VIS spectral range was excited with Ar^+ laser type 543-AP-A01 (Melles-Griot, USA). In particular: the line 488 nm was used. Deep-UV excitation was done by means of semiconductor laser FQCW-266-10 (CryLas GmbH, Germany). The wavelength of laser line was equal to 266 nm. The power of the excitation light was not larger than 1 mW on the sample for each excitation wavelength.

2.3. Experimental methodology

Two types of Raman measurements were performed:

- the dependence between maximum position of one-phonon Si Raman line and the temperature — reference data;