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Application of electrostatic force microscopy in nanosystem diagnostics

TEODOR P. GOTSZALK[1*], PIOTR GRABIEC[2], IVO W. RANGELOW[3]

[1]Faculty of Microsystem Electronics and Photonics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

[2]Institute of Electron Technology, al. Lotników 32/46, 02-668 Warszawa, Poland

[3]Institute of Technological Physics, IMA, University of Kassel, Heinrich Plett Str. 40, 34132 Kassel, Germany

The current state of art of electrostatic force microscopy is described in the paper. The principle of electrostatic force operation enabling one to analyse local voltage distribution and capacitance is presented. The design and properties of electrostatic force microscopy microprobes are discussed. The application and manufacturing process of piezoresistive cantilevers with conductive tips and of silicon beams with metallic probe are presented. In order to show the capabilities of electrostatic force microscopy methods of investigations of local voltage distribution on surfaces of microelectronic integrated circuits (IC) are described. Improvements of electrostatic force microscopy and of other electrical methods based on scanning probe microscopy confirm an increasing interest in electrical probing at the nanometre scale.

Key words: *electrostatic force microscopy; nanosystem; voltage distribution; capacitance*

1. Introduction

A rapid progress in nanotechnology has been observed over the past twenty years. This progress has also been influenced by the development of new diagnostic methods aimed at testing fabricated nanodevices and materials. In nearly all these investigations, nanometre local resolution of the experiments performed and extremely high measurement sensitivity are needed, as high as those established in macroscale investigations. One of the best known techniques which enables surface measurements with the requirements defined above is the scanning probe microscopy. The development of this

[*]Corresponding author, e-mail: Teodor.Gotszalk@pwr.wroc.pl.

technique was stimulated by the invention of first scanning tunneling microscope (STM) by Binnig and Rohrer in 1981 [1]. Based on the design of STM, the first atomic force microscope (AFM) was developed in 1986 [2]. In this way, the era of structural analysis of surface properties using the scanning probe microscopy begun. Atomic force microscopy, in which force interactions acting on the microtip located upon a spring cantilever on the length scale from 10^{-11} to 10^{-7} are monitored, belongs to scanning probe microscopy methods. In 1988 Martin et al. [3] developed an atomic force microscopy based technique which enabled measurements of electrostatic forces and capacitances between the conductive tip and the surface with spatial resolution of 100 nm. This technique was also applied for potentiometry [4, 5] and detection of charges [6]. In 1991, Abraham et al. [7] demonstrated for the first time that dopant profiles in the range of concentrations between 10^{15} and 10^{20} cm^{-3} can also be measured in a nondestructive manner by means of an electrostatic force microscope with capacitive detection. However, the measurement possibilities are strongly dependent on the parameters of the micro- and nanoprobes applied and on the measurement setup. In this paper, we present a general principle of electrostatic force microscopy (EFM). We demonstrate the application of this technique in voltage measurement on the surface of a microelectronic integrated circuit. Additionally, we present electrostatic force microscopy nanoprobes with conductive microtips which were applied in our experiments. We also consider noise and sensitivity of the developed experimental methods.

2. The principle

In electrostatic force microscope (EFM), the electrostatic forces between the cantilever nanotip and the surface are measured. To maintain the distance over the investigated surface, the cantilever vibrates at its resonance frequency. Due to van der Waals forces, the beam vibration amplitude changes and the microscope controller defines the cantilever height over the sample using a piezoelectric actuator. Simultaneously, in order to measure electrostatic interactions in this setup (Fig. 1), we applied a voltage, consisting of an AC and a DC components: $U = U_{dc} + U_{ac}\sin(\omega t)$ between the tip and the sample which gives rise to an electrostatic force given by:

$$\begin{aligned} F &= \frac{1}{2}\frac{dC}{dz}(U_{dc} + U_{ac}\sin(\omega t))^2 \\ &= \frac{1}{2}\frac{dC}{dz}[(U_{dc}^2 + \frac{1}{2}U_{ac}^2) + 2U_{dc}U_{ac}\sin(\omega t) + \frac{1}{2}U_{ac}^2(1 - \sin(2\omega t)], \\ &= \frac{1}{2}\frac{dC}{dz}(F_{dc} + F_{\omega} + F_{2\omega}) \end{aligned} \qquad (1)$$

where C is tip-sample capacitance and ω is the voltage frequency.

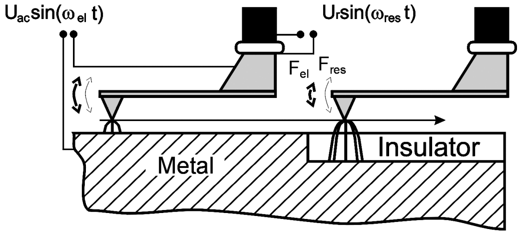

Fig. 1. Electrostatic force microscopy
– a general principle

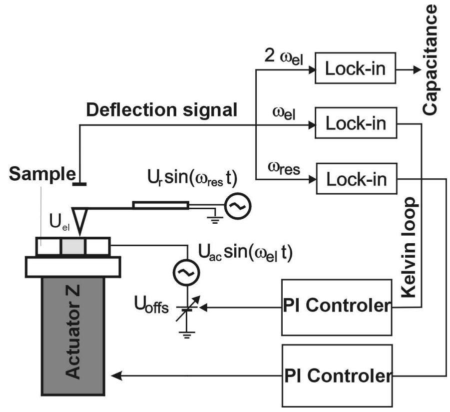

Fig. 2. Experimental setup
of an electrostatic force microscope

In the force spectrum, three separate frequency components are observed: F_{dc}, F_{ω}, $F_{2\omega}$, which can be measured selectively using lock-in amplifiers. Note that in order to measure the DC potential on a specimen, a sum of auxiliary DC and AC voltages is applied to the conductive cantilever microtip (Fig. 2). The oscillation of the cantilever with the frequency ω should be balanced to zero by controlling the auxiliary DC voltage in a feedback loop. In this way, the DC voltage applied to the microtip corresponds to the voltage on a specimen.

3. Electrostatic force microscopy microprobes

In first electrostatic force microscopy experiments, metal wires fabricated by electromechanical etching were used. Relatively high radii of the cantilever tips and, additionally, large cantilever spring constants and their low resonance frequencies did not make them suitable for routine applications. In later experiments, commercially available highly doped silicon cantilevers were applied in investigations of electrical surface parameters. However, the spatial resolution of 50 nm in surface investigations and the high mechanical wear were not sufficient in many applications. In our experiments, two kinds of electrostatic force microscopy sensors have been employed: piezoresistive silicon cantilevers and silicon cantilevers with metalic tips. Most of EFM systems require optical techniques to detect a subnanometre motion of the microtip. From the demand for simplifying the EFM head, an idea came to build the cantilever with an integrated deflection detector and the conductive microtip isolated from the cantilever body. The microprobe, fabricated in the silicon on insulator (SOI) technology, integrates the piezoresistive bridge deflection sensor whose resistivity changes when the cantilever is bent [8]. In this way, an electrical signal corresponding to the beam deflection is measured and can be fed into a standard microscope control unit.

The device developed is shown in Fig. 3. The dimensions of the sensor are: the length 600 μm, width 210 μm, thickness 15 μm, which corresponds to the spring constant of 113 N/m and the beam resonance frequency of 50 kHz. The voltage measurement sensitivity is limited by the relative high spring constant amounting 50 mV for the design described.

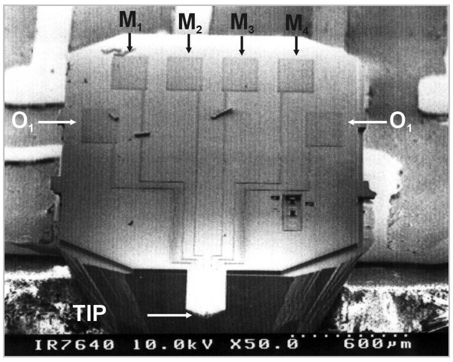

Fig. 3. Piezoresistive cantilever with conductive tip for electrostatic force microscopy. M_1–M_4 are metalization pads for piezoresistive sensor, O_1 – connections strips to the conductive tip

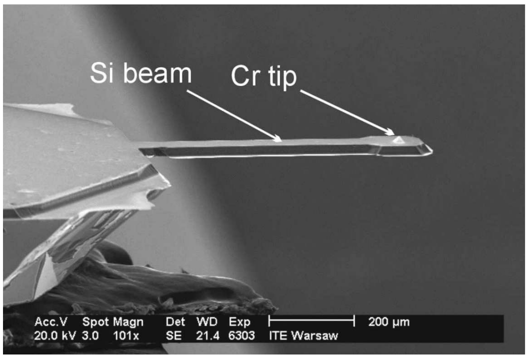

Fig. 4. Microfabricated cantilever with metallic tip for the electrostatic and capacitance microscopy [9]

To perform more sensitive experiments, we developed a cantilever with a metallic tip [9]. The sensor was fabricated in the complementary metal oxide semiconductor (CMOS) technology combined with the surface and bulk micromachining. The microprobe consists of a pyramid-shaped Cr tip and a metal line deposited on a silicon beam (Fig. 4). The narrow metal strip located on the cantilever backside is used for the electrical connection between the microtip and the microscope electronics. The metal cantilever tip makes the sensor suitable in semiconductor investigations like dopant profiling based on capacitance–voltage (*C–V*) and electrostatic force measurements. The beam deflection occuring when the cantilever is bent under van der Waals and electrostatic interactions is observed using an optical position sensitive detector with the resolution of 0.05 nm in the band width of 100 Hz.

4. Experimental

The sensitivity of the electrostatic interactions measurement using the piezoresistive cantilever was tested. The Wheatstone piezoresistive bridge cantilever was placed 100 nm above the surface (the distance was controlled by a fibre interferometer) and the beam resonance curves were recorded for the tip-surface voltages of $U = 0$ V and $U = 10$ V. The electrostatic attractive interaction acts as an additional spring shifting the beam resonance frequency to lower values. The resonance frequency shift for the parallel tip–surface capacitor is given by the equation:

$$\Delta f = f_r \frac{\varepsilon_0 A U^2}{2kz^3} \tag{2}$$

For the beam with the geometry of l = 600 μm, b = 210 μm, d = 15 μm, spring constant k = 113 N/m, resonance frequency f_r = 50 kHz, cross-sectional area A = 0.1 μm^2, the resonance frequency shift Δf can be estimated to amount to 15 Hz. In Figure 5, the resonance curves measured for the tip-surface voltage of 0 V and 10 V are shown. The resonance frequency shift of 20 Hz was detected under the voltage difference of 10 V.

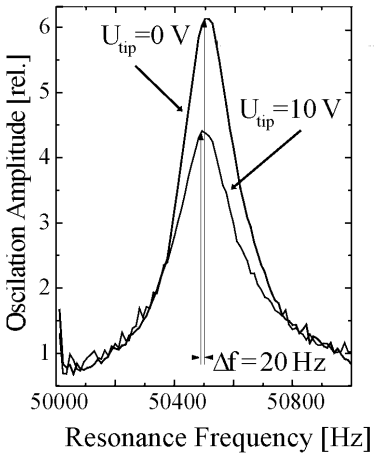

Fig. 5. Resonance frequencies of the piezoresistive cantilever with a conductive tip under various probe voltages [8]

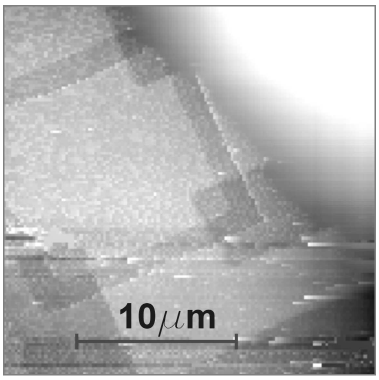

Fig. 6. Topography of the MEMS piezoresistive force detector measured with the fabricated microprobe

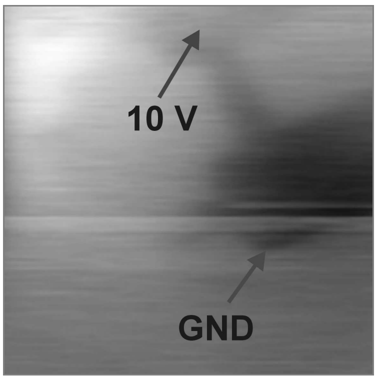

Fig. 7. Electrostatic force microscopy map of the voltages in the area shown in Fig. 6

To present the possibilities of the voltage measurement, we applied the cantilever with a metalic tip in the test measurement of the dc potential on an IC surface. The sample contains four implanted resistors which are connected to form a Wheatstone bridge (Fig. 6). The sample topography was measured based on the resonance vibration reduction under the influence of the van der Waals force interaction. While scanning the surface we also observed the electrostatic force F_ω, when only one bridge resistor was supplied with the voltage of 10 V. The voltage drop along the implemented resistor is clearly seen in Fig. 7.

5. Conclusions

The electrostatic force microscopy based on the scanning probe microscopy methodology, is an established technique for local investigations on insulating and conductive nanosystems. Using this technique, one can study not only the topography but also obtain information about: (i) local work function on the surface (so-called Scanning Kelvin Microscopy), (ii) capacitance between the microtip and the surface, related to the dielectric surface parameters or dopant profiles, (iii) voltage behaviour on an operating structure. The features presented make electrostatic force microscopy important as a tool in nanotechnology and failure analysis. An improvement in spatial resolution is connected with the fabrication and application of cantilevers with spring constants inferior to 5 N/m, upon which tips with the radius of 15 nm are located. The increased measurement sensitivity can be achieved by applying electrical modulation voltage to the tip whose frequency corresponds to a higher eigenmode resonance beam oscillation.

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