BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES
Vol. 56, No. 1, 2008

Conductive atomic force microscope for investigation of thin-film gate insulators

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Abstract. In modern microelectronics progress has been made towards low power ultra large-scale integration (ULSI), and nano-structure devices such as single electron transistors and quantum dots. In this technology application of new materials, which includes high-κ dielectrics for the MOSFET transistors, with extraordinary purity and uniformity is required. Failure analysis and reliability investigations of such films very often requires high-resolution local measurements of electrical surface parameters. This kind of experiments can be performed using conductive atomic force microscopy, which provides simultaneous measurement of surface topography and current flowing through the investigated layer. In order to acquire reliable data, there was designed a precise measurement and control system, which included a low-noise current-to-voltage converter of picoampere resolution, a scanning stage with control electronics and a data acquisition system. In the paper we describe the architecture of the designed and applied experimental set-up. We also present results of simultaneous measurements of topography and current on gold and highly oriented pyrolytic graphite (HOPG).

Key words: AFM, conductive probe, thin-film oxides.

1. Introduction

Only few years ago miniaturisation was the best way to increase the speed of integrated circuits. The smaller were the MOSFETs and the shorter was their channel, the faster was the chip. As for now, in the laboratories there is done a research on transistors made in 45-nm technology, which means that the length of the channel is less than 25 nm. Since 1997 the length has been reduced four times. The thickness of the gate insulation had to be correspondingly decreased which led to serious increase of the probability of breaking the insulation. In the newest devices the insulation made of thermal SiO_2 has the thickness of 1.2 nm which means that it is made of only a few atomic monolayers. The leakage connected with the decreased thickness causes a significant increase of power dissipation that, in extreme cases, disqualifies the integrated circuit from the economical point of view because of its unacceptable power consumption [1].

Now, new materials are being searched, which leakability would be decreased and permittivity increased. Under research there are especially: hafnium dioxide (HfO_2), zirconium dioxide (ZrO_2), lantanium trioxide (La_2O_3) and silicon oxynitrides (SiO_xN_y). Their electrical permittivity is up to 8 times greater than permittivity of silicon dioxide [2].

Gate insulations made of those materials may be better than those made of SiO_2 due to better uniformity, less leakability and less roughness. Nonetheless, a deep research in electrical and mechanical properties of layers made of the new materials is needed, including local measurement of leakage current and topography with as large resolution as possible. A perfect tool for such measurements is a conductive atomic force microscope (C-AFM), also called conductive probe atomic force microscope (CP-AFM), which is a classical contact AFM equipped with a conductive probe. It enables simultaneous measurement of topography and current that flows between the sample and the microprobe.

In the paper we present the architecture of the conductive atomic force microscope, developed in our laboratory, and results of test measurements on gold and HOPG surfaces.

2. Architecture of a conductive atomic force microscope

To be able to analyse and diagnose thin-film gate insulators we have constructed an atomic force microscope working in static (contact) mode with optical detection of cantilever deflection. The light source is a semiconductor laser with a wavelength of $\lambda = 635$ nm. The laser beam is focused on the cantilever using a specialised optical system. Having been reflected from the backside of the cantilever the beam is traced to a four-sectional photodetector. Any deflection of the cantilever, resulting from its interaction with the sample surface, causes a change of the point illuminated on the photodetector. This means a change in the output electrical signal (the difference between the signals from upper and lower sections of the detector). The signal is maintained at a fixed

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level by a proportional-integral-derivative (PID) controller, which controls the vertical position of a piezoelectric scanner. The output signal of the PID controller gives us information about the topography of the surface. The horizontal position of the sample is changed by a two-channel high-voltage amplifier, controlled by software (via a PC card) that have been developed in our laboratory. The software is also used for data acquisition [3].

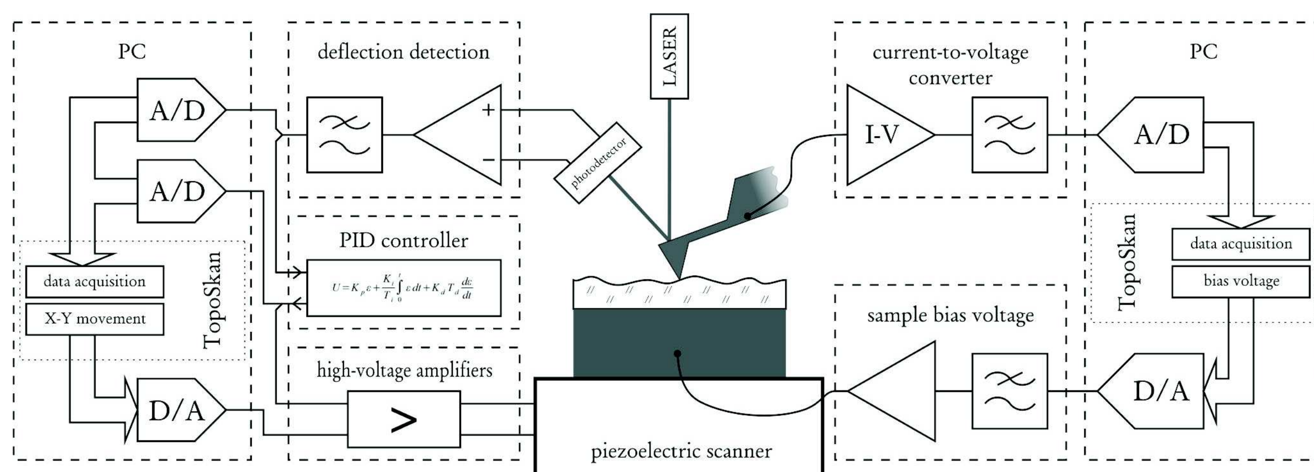


Fig. 1. Schematics of a conductive atomic force microscope, with topography measurement part on the left and current measurement part on the right

We have equipped the system with a conductive probe. We use three types of probes:

- Pointprobe® CONTPt, length: 447 μm, width: 46 μm, thickness: 1.9 μm; made of silicon with 23-nm PtIr5 coating, tip curvature less than 25 nm and spring constant of 0.16 N/m [4];
- Pointprobe® EFM, 225 μm × 28 μm × 3 μm, made of silicon with 23-nm PtIr5 coating, tip curvature: less than 25 nm, spring constant: 1.8 N/m [4];
- Pointprobe® CDT-FMR, 225 μm × 28 μm × 3 μm, made of silicon with 100-nm policrystalline boron-doped diamond coating, tip curvature: 100–200 nm, spring constant: 2.8 N/m [4].

With the scanning system we have integrated a precise current-to-voltage converter for the detection of the current flowing between the microprobe and the surface. The current flow is forced by applying voltage to the sample, and is controlled by the microscope control software. The architecture of the complete system is shown in Fig. 1.

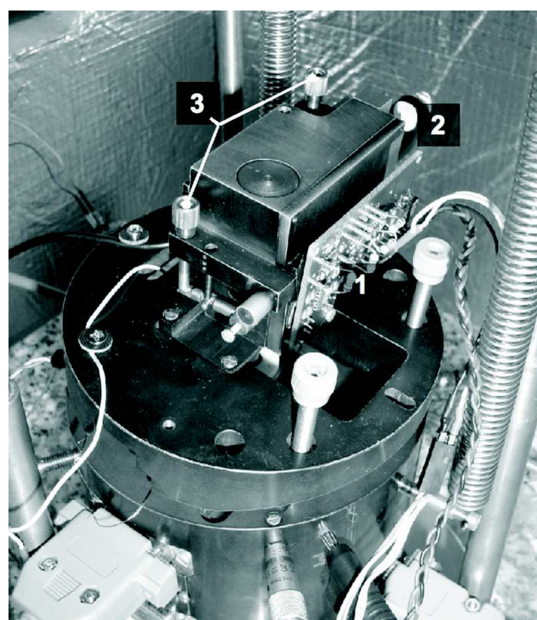


Fig. 2. Measurement head of a conductive atomic force microscope (1 – photodetector with electronic circuit, 2 – laser with optics, 3 – precision beam-tracing screws

3. Measurement set-up

3.1. Mechanical elements. The measurement head of the conductive atomic force microscope includes (see also Fig. 2):

- system for laser handling and positioning,
- probe holder that enables current measurements,
- mirrors to trace the laser beam,
- holder of photodetector with electronic circuit,
- CCD camera holder (optional).

3.2. Noise reduction. A system that reduces the background noise is an important part of every scanning probe microscope. In order to perform reliable measurements, disturbance caused by the building and other noise: acoustic, electromagnetic and thermal, must be decreased. To reduce the influence of vibrations, the measurement head is suspended on springs coming down from three poles, placed on a granite plate. The plate stands on another set of springs inside a dedicated measurement chamber with acoustic and thermal isolation. In

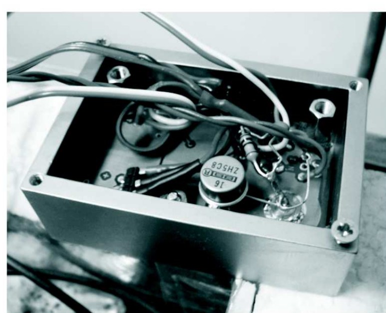
addition, the chamber is placed on a set of concrete blocks of 200 kg mass. The resonant frequency of the double-spring system should be as low as possible, therefore proper choice of springs is crucial.

4. Electronic devices

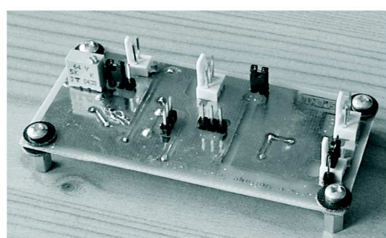
For the measurement of the current flowing through the tip there have been designed two devices: a current-to-voltage converter with picoampere resolution and a stable bias voltage source.

The main part of the current-to-voltage converter is OPA128 made by Burr-Brown, an operational amplifier with extremely low input bias current, which is less than 75 fA [5]. In the feedback loop there are used resistors, which resistance ranges from 50 MΩ to 1 GΩ. There is also an amplifier with gain of 100 V/V, which corresponds with the overall sensitivity of the converter ranging from 5 to 100 mV/pA. The effectivity of the device has been increased by applying an isolation amplifier ISO124 [6] and a low-pass filter with cut-off frequency of 300 Hz.

The bias voltage source enables applying voltage to the sample using the measurement control software, directly from the PC computer, but also it is possible to use a voltage reference and a potentiometer, which are a part of the device. To reduce the noise caused by the PC card there are used: a low-pass filter and an isolation amplifier circuitry. In Fig. 3 the designed current-to-voltage converter and bias voltage source are presented.



(a)



(b)

Fig. 3. Electronic devices designed for current measurements: (a) current-to-voltage converter (b) bias voltage source

In order to control the scanning and data acquisition processes the following auxiliary electronics components have been designed and applied:

- proportional-integral-derivative (PID) controller, which has been implemented as an analog circuit, in which gain of every term is modifiable;
- three high-voltage amplifiers with output range of ± 90 V to amplify the control signals for piezoelectric scanner position in three axes (XYZ) and enabling surface scanning of 10 μm $\times$ 10 μm $\times$ 3 μm;
- driver of the DC mike, used for coarse approach of the measurement head to the probe;
- low- and high-voltage suppliers.

5. Results

5.1. Topography and current. As it was already mentioned in section 2, to measure topography we record the output signal of the PID controller. The signal maintains the deflection of the cantilever by controlling the Z-movement of a piezoscanner (which is a piezotube in our system), positioned under the sample. Therefore, a hollow on the surface causes the piezotube to expand, while any hill causes it to shrink. The measurements, results of which we present, have been made using piezoscanners with Z-movement sensitivity in the range of 110–220 nm/V (this means that every 1-V change of PID controller output causes a 110–220 nm change in piezoscanner vertical position).

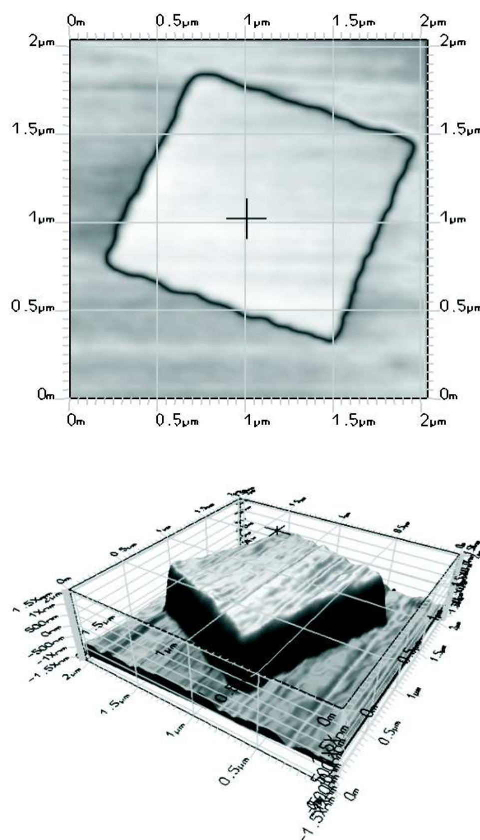


Fig. 4. Topography of TGQ1 calibration grating observed using the designed system (CONTPt probe). Dimensions of the visible detail: 1.5 μm $\times$ 1.5 μm $\times$ 19.5 nm

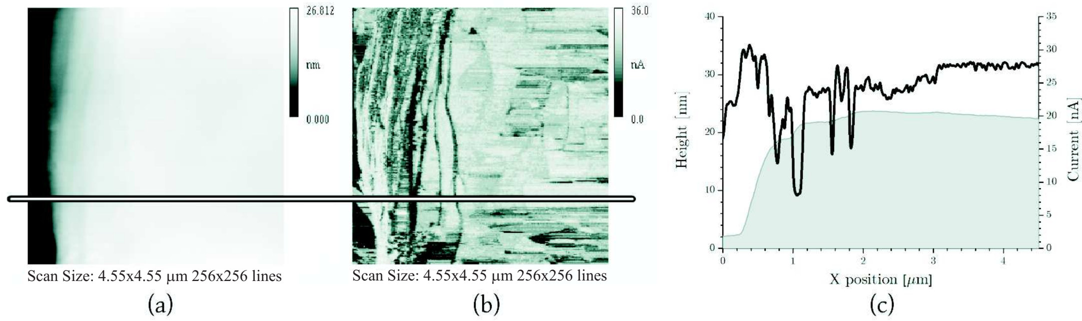


Fig. 5. Simultaneous (a) topography and (b) current measurement on a HOPG sample, made using an EFM probe. In addition, a (c) section is shown. Scan area of about $4.5\ \mu$m $\times$ $4.5\ \mu$m

As we use a conductive atomic force microscope, besides the topography signal we record also the output signal of the current-to-voltage converter. The signal is proportional to the current flowing between the cantilever tip and the sample, according to following relationship:

$$V_{IV} = k_V \cdot (-IR_{IV}), \tag{1}$$

where: V_{IV} – output signal of the current-to-voltage converter, k_V – gain of the second stage of the converter, I – measured current, R_{IV} – resistance of the resistor in the first stage of the converter. If there is a need of measurement in direct electrical contact (i.e. without any insulator), we use a 20.5 kΩ resistor, serially connected to the cantilever.

As test samples we have used: for topography observations – calibration gratings TGQ1 by NT-MDT [7] with $1.5\ \mu$m squares, 19.5 nm high (Fig. 4), and for current measurements – an Au-on-Si sample and highly oriented pyrolytic graphite (HOPG) sample (Fig. 5). The results of simultaneous current and topography measurements using EFM cantilevers are shown in Fig. 5. In the topography image (Fig. 5a) atomic steps of HOPG can be observed. The observed height of the steps is of about 2 nm, which corresponds to 5–6 atomic layers. The topography image corresponds to the current measurements (Fig. 5b), which were recorded at tip voltage of 10 mV. Furthermore, dependence between conductivity and atomic structure of the graphite can be seen, being revealed as different shades of grey on the current flow image, which may correspond to different conductivity resulting from different mobility of electrons from π orbitals, as described in [8]. In addition, there is less current flowing on the edges of smaller steps than on flat surface (Fig. 5c). This in our opinion may correspond to charge depletion regions, present just after the step, which are typical for armchair-type lattice edges. In contrary, higher current on the other edges may result from presence of edge states, which are a property of zigzag-type lattice edges [8].

5.2. Contact resistance. We have measured contact resistance (tip–sample contact) using current-voltage (I-V) spectroscopy in different points on gold and HOPG samples. There was a 20.5 kΩ resistor serially connected to the cantilever. The samples were biased in the range of $-10 \div 10$ mV (the exact range of every measurement varied). Results of the measurements for different probes are shown in Table 1 and in Fig. 6. The results are of the same order of magnitude as those presented for similar probes in [9].

Table 1
Results of contact resistance measurements for different probes

Probe	Sample	
	Au on Si	HOPG
CONTPt	1.0– 3.6 kΩ	10.2–13.2 kΩ
EFM	0.6– 1.6 kΩ	19.0–28.3 kΩ
CDT-FMR	7.7–12.5 kΩ	12.7–20.3 kΩ

5.3. Load force. The load force, given in Table 2, was calculated from F vs. V_{sp} characteristics, where F – the load force, V_{sp} – setpoint for the PID controller. In this calibration process the control setpoint was modulated and the output of the PID controller, which corresponded to the piezoactuator length, was recorded. Based on these investigations the load force between the microtip and the surface can be calculated. Example F vs. V_{sp} graph can be seen in Fig. 7.

Table 2
Results of load force calibration for different probes

Probe	Load force
CONTPt	18– 31 nN/V
EFM	195–310 nN/V
CDT-FMR	210–380 nN/V

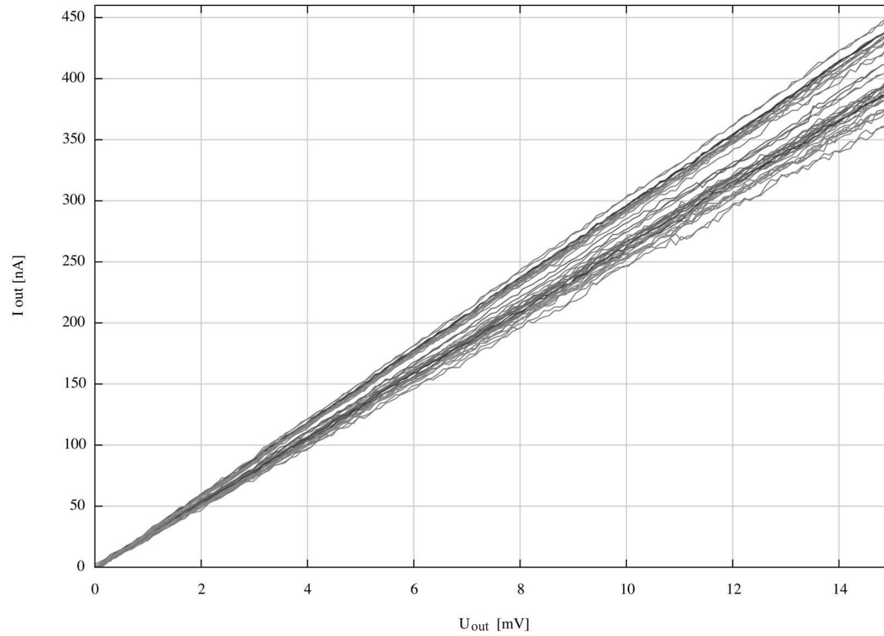


Fig. 6. Measurement of contact resistance between HOPG surface and the tip of CDT-FMR cantilever

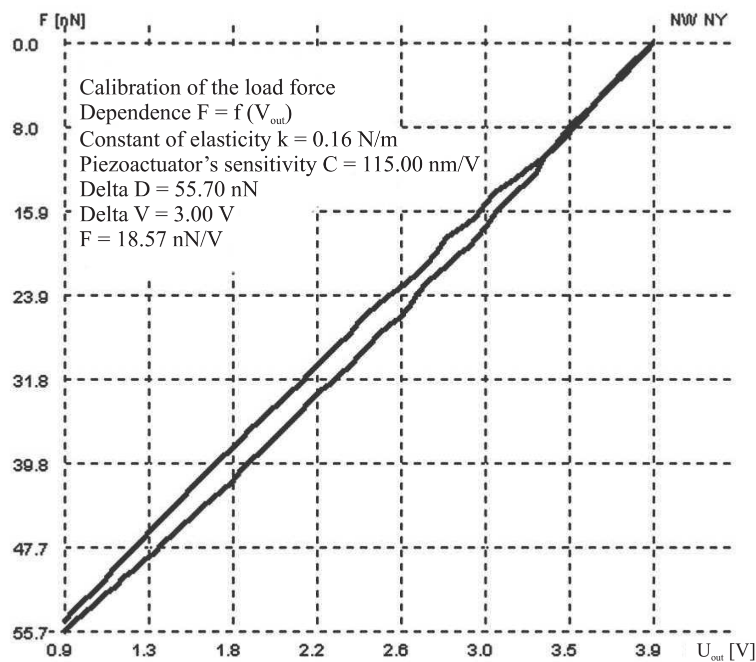


Fig. 7. Calibration of the load force acting on the CONTPt cantilever on HOPG surface

6. Summary

In the article we presented construction of a conductive atomic force microscope, designed for investigation of thin-film oxide gate insulators. We described mechanical parts of the measurement head and electronic devices, which the microscope driver consists of. We also presented example results including simultaneous measurement of topography and current.

The research on the thin-film oxides have already started and the results will be presented shortly.

Acknowledgements. The research is funded by the Ministry of Science and Higher Education of the Republic of Poland within grant no. 3T11B01127. In the academic year 2006/2007 Grzegorz Wielgoszewski was a scholarship holder within the "Polish Talents" program, organised by TP Group Foundation.

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