Paper

Piezoresistive sensors for atomic force microscopy – numerical simulations by means of virtual wafer fab

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Abstract — An important element in microelectronics is the comparison of the modelling and measurements results of the real semiconductor devices. Our paper describes the final results of numerical simulation of a micromechanical process sequence of the atomic force microscopy (AFM) sensors. They were obtained using the virtual wafer fab (VWF) software, which is used in the Institute of Electron Technology (IET). The technology mentioned above is used for fabrication of the AFM cantilevers, which has been designed for measurement and characterization of the surface roughness, the texturing, the grain size and the hardness. The simulation are very useful in manufacturing other microcantilever sensors.

Keywords* — *atomic force microscopy, piezoresistive sensors, technology simulation, technology characterization.

1. Introduction

Scanning probe microscopy (SPM), based on the interaction of the Van der Waals forces, is a breakthrough technology that allows three-dimensional imaging and measurement of structures from the atomic to the micron scale. Atomic force microscopy, which followed few years later, measures the attractive or repulsive forces between tip and sample. AFM can be used for measurements of conductive and non-conductive samples. The typical applications are:

- semiconductors – characterization of silicon surface roughness, implant carrier distribution, defect in layers, sub-micron geometry devices and mask development;
- data storage and magnetic materials – characterization of topography and magnetic domains with very high resolution;
- biotechnology – analysis of cellular motion, viscoelasticity and morphology, protein structure and wide variety of biomaterials;
- electrochemistry – real-time imaging of surface chemical processes, electropolishing and corrosion;
- material characterization – analysis of surface roughness, surface stiffness, surface structure, grain size and defects.

Characterization of the interfacial phenomena like friction and wear is particularly important for the effective design of microdevices (Fig. 1).

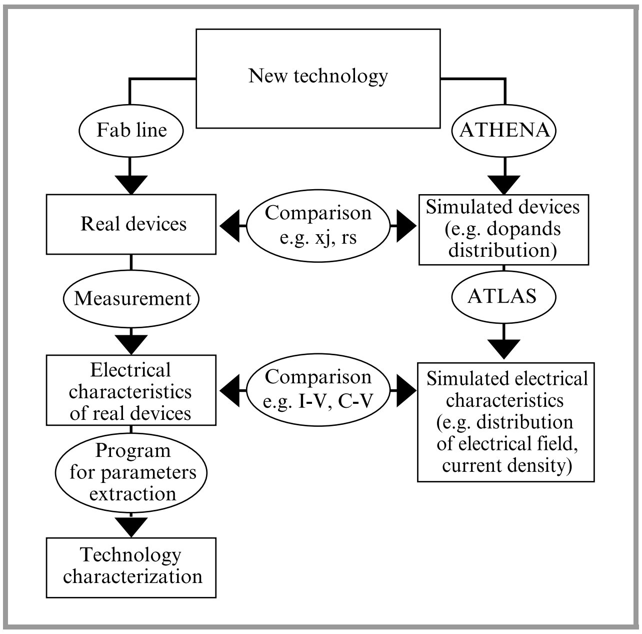

Fig. 1. Correlation between technology process characterization and simulation.

2. Theory

The most typical construction of the AFM is a silicon cantilever with an integrated piezoresistive deflection detector. The displacement of the cantilever is sensed by the piezoresistive Wheatstone bridge. The mechanical stress change the resistance of the piezoresistors. To obtain optimal maximal resistivity variation the Wheatstone bridge is located in the crystal orientation [110] (Fig. 2). The bridge output voltage U_{out} due to electrical scheme (Fig. 3) can be calculated:

$$U_{out} = \frac{12\xi l U}{b d^2} F \,,$$

where ξ – piezoresistive coefficient, l – cantilever length, b – cantilever width, d – cantilever thickness, U – supply voltage, F – force.

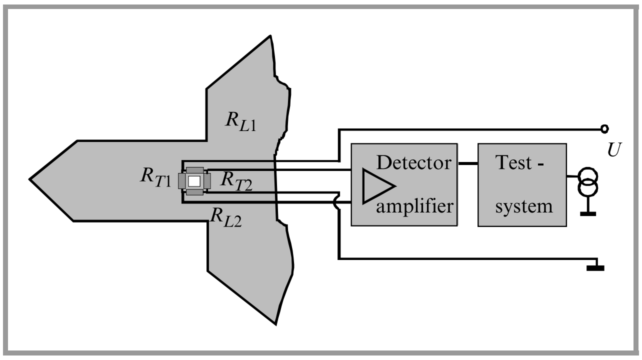

Fig. 2. Electrical scheme of the piezoresistive cantilever measurement system.

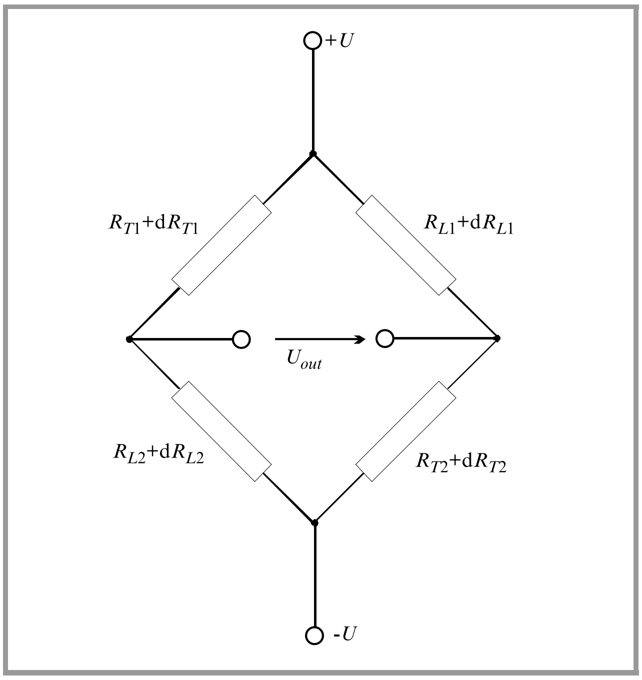

Fig. 3. Electrical scheme of the piezoresistive Wheatstone bridge.

The equation describes the piezoresistive cantilever in the contact mode. In this method forces from 1 nN to 100 nN acting on the tip can be measured. Bridge output voltage U_{out} strong depends also on the beam geometry.

3. Simulation

Every technological experiment must be preceded by detailed considerations of the assumptions, proposed solutions and its expected results. The technical experience supported by advanced CAE techniques and software is very relevant at this point. Such an approach is a common practice in IET, where the simulation package developed by SILVACO (USA) is used. Two simulation tools: ATHENA/SSUPREM4 and ATLAS/SPISCES are the basic parts of our system (Fig. 4).

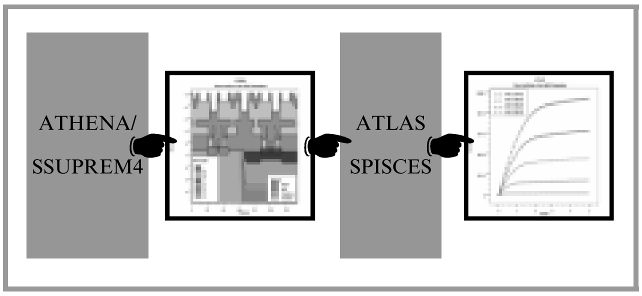

Fig. 4. Simulation package developed by SILVACO (USA).

ATHENA is a very complex program for numerical simulation of sequences of technological processes. It enables both one- and two-dimensional simulation of the following processes: diffusion, oxidation, deposition, chemical and plasma etching and ion implantation. The models of these processes are controlled by a great number of parameters which determine the model's complexity on their characteristics.

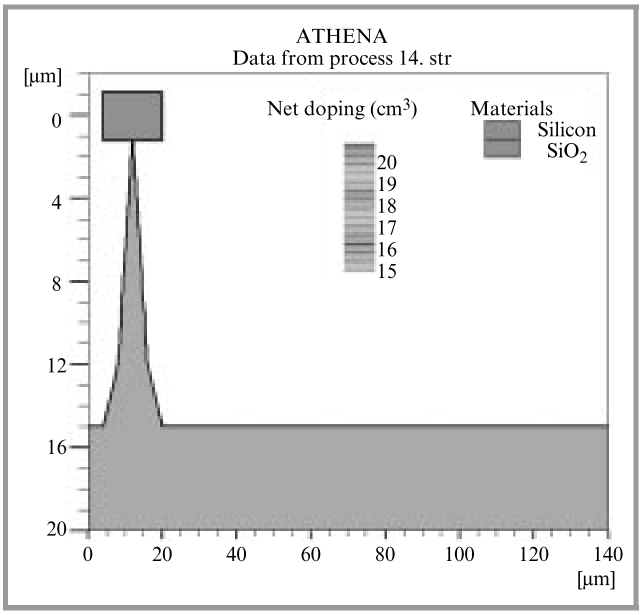

Fig. 5. Cross-sections of the piezoresistive cantilever – tip etching.

ATLAS is a software for numerical two-dimensional simulation of electrical characteristics of semiconductor devices. It enables calculation of DC, AC and transient characteristics.

ATHENA/SSUPREM4 input data file contains a detailed description of the material used as a bulk of the device, its crystallographical orientation, type of the conductivity and resistivity. Modelling of the subsequent processes is the next stage of simulation. The engineer determines the processes parameters, like operations duration, the temperatures, processes atmosphere, doping concentrations, type, stechiometry and the density of the deposited layers, doses

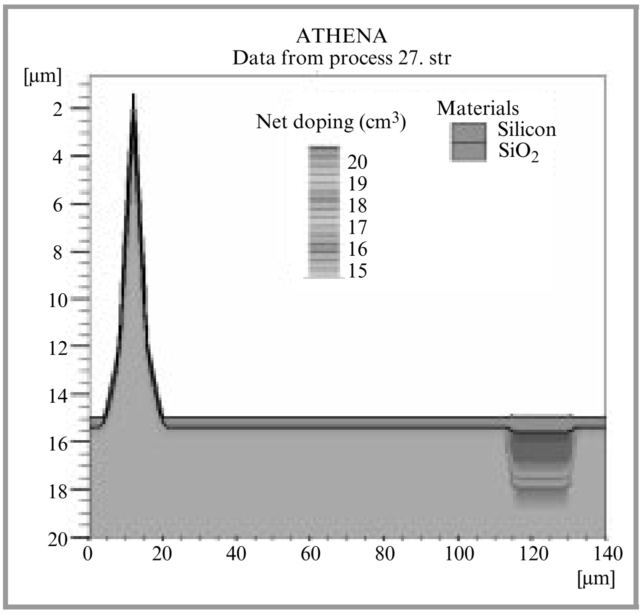

Fig. 6. Cross-sections of the piezoresistive cantilever – n$^+$ diffusion.

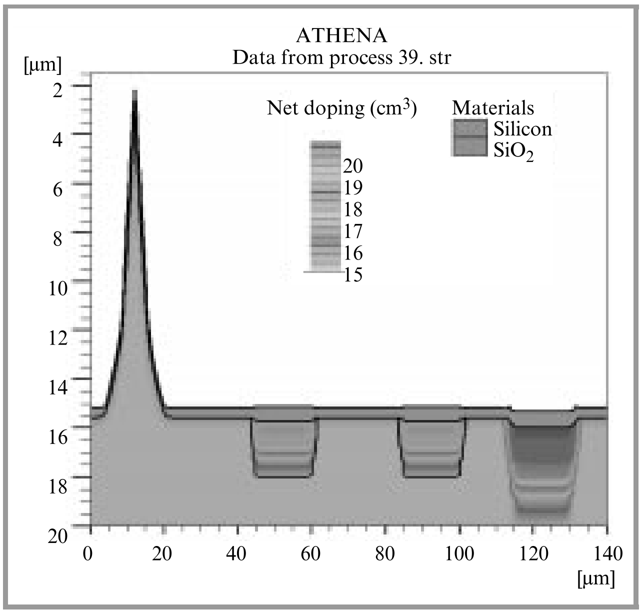

Fig. 7. Cross-sections of the piezoresistive cantilever – p$^+$ diffusion.

and the energies of ion implantations. After these calculations we obtain the doping concentration distributions, junctions depths and the layers thicknesses in the final structure. Figures from 5 to 9 represent cross-sections of the piezoresistive AFM cantilever simulated by mean virtual wafer fab.

The output data of processes simulation establish the input data for ATLAS/SPISCES program. At the moment all the electrodes in the devices must be defined. Next, the input signals must be determined. After the simulation we obtain a solution which comprises not only device electrical characteristics but spatial distributions of variables like potential and current density as well.

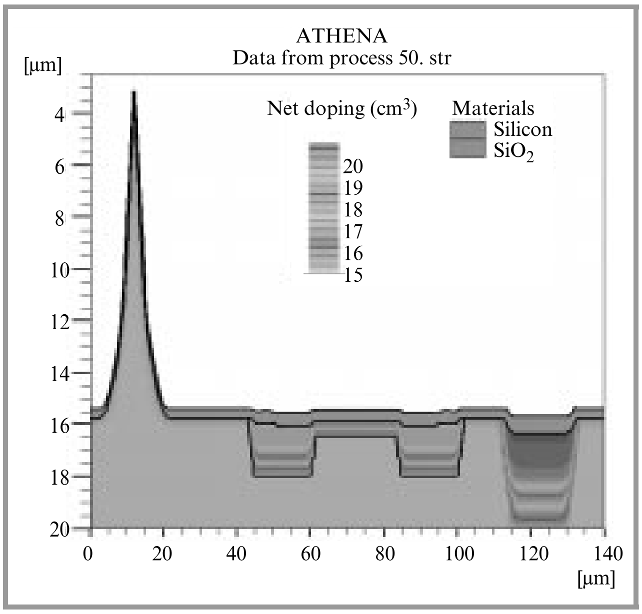

Fig. 8. Cross-sections of the piezoresistive cantilever – piezoresistors diffusion.

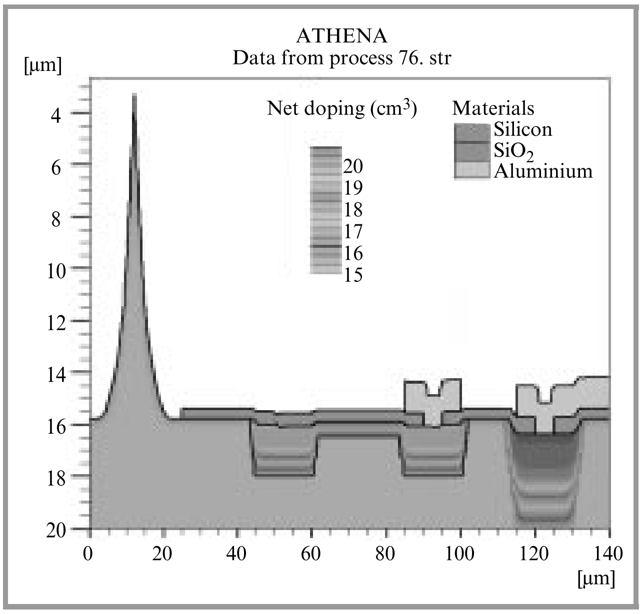

Fig. 9. Cross-sections of the piezoresistive cantilever – final structure.

The development of a new technological sequence is a very difficult task. The engineer must be familiar with many complicated physical phenomena, which are dependent on many input parameters.

4. Fabrication

The fabrication process is based on the double side silicon micromachining process. Double-side polished

<100>-oriented, $3 \div 7\ \Omega$cm silicon wafers were used as the starting material. Next, standard CMOS processing like oxidation, phosphorus and boron diffusion, ion implantation, dry and wet etching, insulator and aluminum film deposition and photolithography were sequentially applied to form n^+ and p^+ diffusion connecting paths, piezoresistors, contact windows and metallic connections. In the following – back side processing sequence a corner compensated membrane pattern was created by two-side photolithography process and anisotropic deep etching of silicon in 30% KOH solution at 60°C, to create 15 μm thick silicon membrane in the future beam area. Finally, the cantilever was defined in the membrane by last photolithography step at the top side of the wafer and silicon dry etching in $SF_6/CHF_3/Ar$ plasma. 50 μm thick photoresist AZ4562 was used to mask piezoresistive circuit and the tip (Fig. 10).

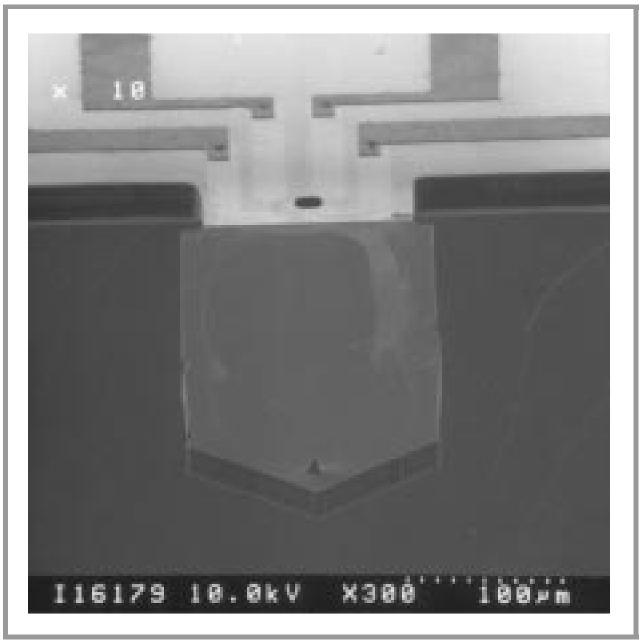

Fig. 10. The SEM picture of the piezoresistive AFM cantilever.

5. Results and discussion

An important element in microelectronics is the comparison of modelling and the measurements results of the real semiconductor devices. Our paper describes the final results of the numerical simulation of the piezoresistive AFM cantilever process sequence and the experimental results. Silicon devices are prepared by performing a sequence of processing steps on a silicon wafer. VWF simulation of the atomic force microscopy sensors should optimize the device parameters, reduce the development time and cost. Programmes for the simulation of semiconductor devices allow to reduce cost of technological experiments. They give better understanding of the complex modern microelectronics. However engineers must be aware of software limitations. The necessity of good correlation of simulated and real data is particularly relevant. It is a very difficult problem, which can be solved only if sufficient knowledge is gathered.

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Andrzej Jakubowski – for biography, see this issue, p. 33.