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FIB/SEM technology in NEMS/MEMS fabrication and investigation

Abstract. *FEI Helios NanoLab 600i microscope with Kleindiek MM3A-EM micromanipulators, controlled by microscope PC connected to Keithley 2400 Source Meter, has been used in our experiments. Due to limited space only several examples of FIB/SEM processes that have been conducted are presented here. They proof the great advantage of this technology in modifying single structures in short time.*

Streszczenie. *Mikroskop FEI Helios600i wraz z mikromanipulatorami Kleindiek MM3A-EM oraz urządzenie Keithley 2400 zostały użyte w naszych eksperymentach. Z powodu ograniczonego miejsca przedstawiono jedynie kilka przykładów procesów z wykorzystaniem technologii FIB/SEM. Największą zaletą tej technologii jest możliwość modyfikacji pojedynczej struktury w krótkim czasie. (**Technologia FIB/SEM w produkcji i badaniach NEMS/MEMS**).*

Keywords: Focused Ion Beam, Scanning Electon Microscope, Micro Electro-Mechanical Systems, Nano Electro-Mechanical Systems.
Słowa kluczowe: Zogniskowana Wiązka Jonów, Skaningowy Mikroskop Elektronowy, Mikro Elektro-Mechaniczny System, Nano Elektro-Mechaniczny System.

Introduction

Nowadays an increase of microelectronic devices complexity can be observed. This kind of devices, often containing micro- and nanomechanical parts, form so called micro- and/or nano electro-mechanical systems (MEMS/NEMS). Due to the complexity mentioned above it is quite difficult to recognize the reason of the microelectronical failure. Usually the micro- and nanoelectronic components are integrated in the substrate and only ohmic connections for wirebonding are on the top of the considered structure. For the complex investigation there is a need to perform volume analyses at the nanoscale regime. In this case the focused ion beam/scanning electron microscope (FIB/SEM) technology seems to be one of the most appropriate investigation tools for the MEMS/NEMS studies. It is quite novel powerful approach for milling and three-dimensional (3D) imaging of samples [1-5].

Using the FIB/SEM it is possible to modify, analyze, repair and test microelectronic devices included in the MEMS/NEMS [6]. The high resolution scanning electron microscope (HRSEM) provides surface observations with 0,9 nm resolution, and allows the failures to be find and the cause of damages often to be recognize, whereas the focused ion beam system enables to mill the material with nanometer precision and makes it really fast and easy, allowing to perform cross section analysis. After precision milling and polishing processes there is a possibility to observe the profile of investigated sample with various SEM technologies.

For the electrical investigations micromanipulators with electrical connections have to be utilized. Circuit tests can be performed by polarization of structures with the use of the micromanipulators. Detected failure, for example gap, can be repaired by focused electron or ion beam deposition induced process of conductive material.

Contrary to the classical methods of the MEMS/NEMS device fabrication, that do not provide any modifications after this process, the FIB/SEM technology can be successfully used for such purpose. By adding and removing well defined volume of material calibration of structures can be performed. It is also possible to change the mechanical properties of structures in a controlled way. The great advantage of FIB/SEM technology is possibility to modify single structure in short time.

Experimental arrangement

The experimental configuration containing FEI Helios NanoLab 600i microscope with Kleindiek MM3A-EM micromanipulators, controlled by microscope PC connected to Keithley 2400 Source Meter, that has been used in our experiments is presented in Figure 1.

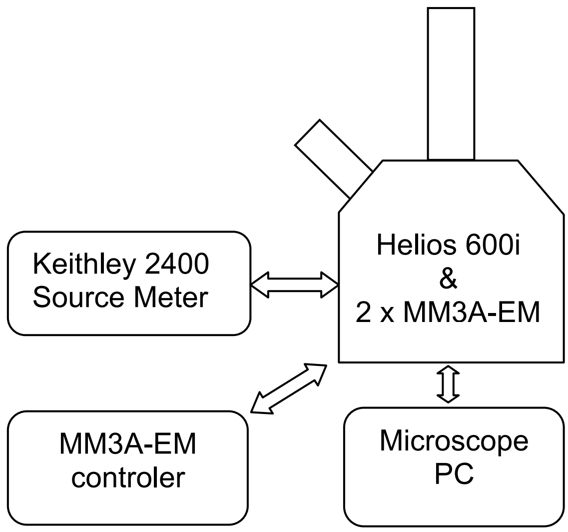


Fig. 1. Schematic representation of experimental arrangement containing FEI Helios NanoLab 600i microscope with Kleindiek MM3A-EM micromanipulators, controlled by microscope PC connected to Keithley 2400 Source Meter

The main parameters of the FIB/SEM are as follows: a) ion column - superior high current performance with up to 60 A/cm^2 beam current density and up to 65 nA max beam current, lowest voltage (500 V) for ultimate sample preparation quality, 2-stage differential pumping and time-of-flight (TOF) correction, b) electron beam resolution - 0.8 nm at 30 kV (STEM), 0.9 nm at 15 kV and 1.4 nm at 1 kV, c) ion beam resolution - 4.5 nm at 30 kV using preferred statistical method and 2.5 nm at 30 kV using selective edge method, d) landing voltage range for electron beam: 350 V - 30 kV and for ion beam: 500 V - 30 kV, e) probe current of electron beam up to 22 nA and of ion beam: 1 pA - 65 nA, f) high precision 5-axes motorized stage - XY: 150 mm, piezo-driven (with X,Y repeatability: 1.0 μm) and Z: 10 mm motorized.

FIB/SEM in MEMS/NEMS investigation: tests and measurements

Figure 2 shows atomic force microscope (AFM) cantilever [7] with bounded electrical connections.

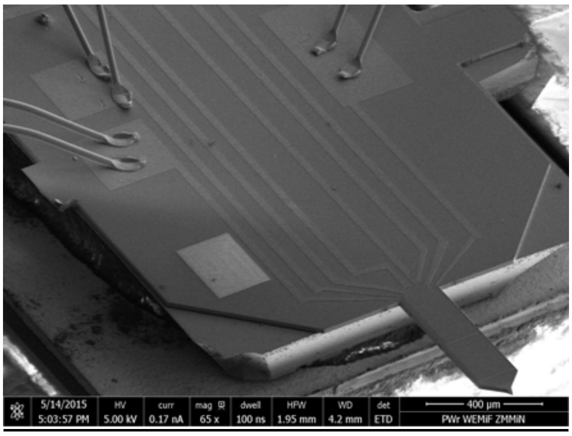


Fig. 2. AFM cantilever with bounded connections

To perform quality test of wire connections without FIB/SEM technology, tear test need to be performed but after this kind of test the connection is usually broken. The force needed for tear the connection is a value that defines the quality of connection. FIB/SEM technology allows to determine the quality of wire connection without ripping. The whole process took about 15 minutes to state quality of bonding. The first step was creating a protection layer of platinum with focused ion beam induced deposition process (Fig. 3).

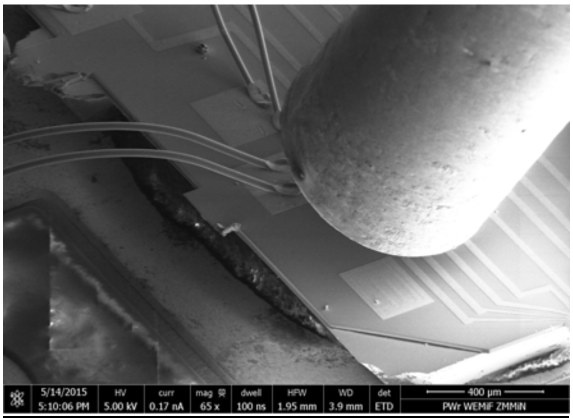
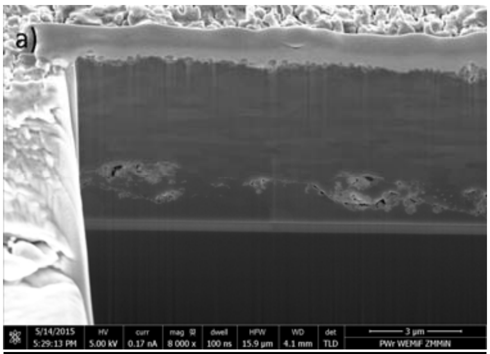


Fig. 3. Focused ion beam induced deposition process of platinum



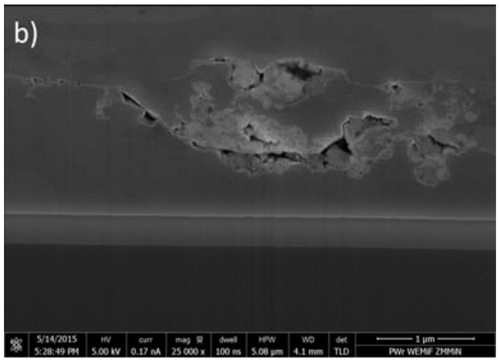


Fig. 4. SEM images of: a) created profile of wire connection, b) ultra high resolution image of crack seen in Fig. 4a

Platinum layer on the top of investigated structure protects even the soft materials. It is worth noting here that ion milling rate is different for various materials. After this step cross section cut is needed to perform. The cut must end on the edge of platinum protection layer. Next to cross section cut a long dwell time polishing has been accomplished, that enabled the profile of wire-pad connection to be analyzed. With ultra high resolution mode of scanning electron microscope the structure of wire, connection and pad can be observed and studied (Fig. 4).

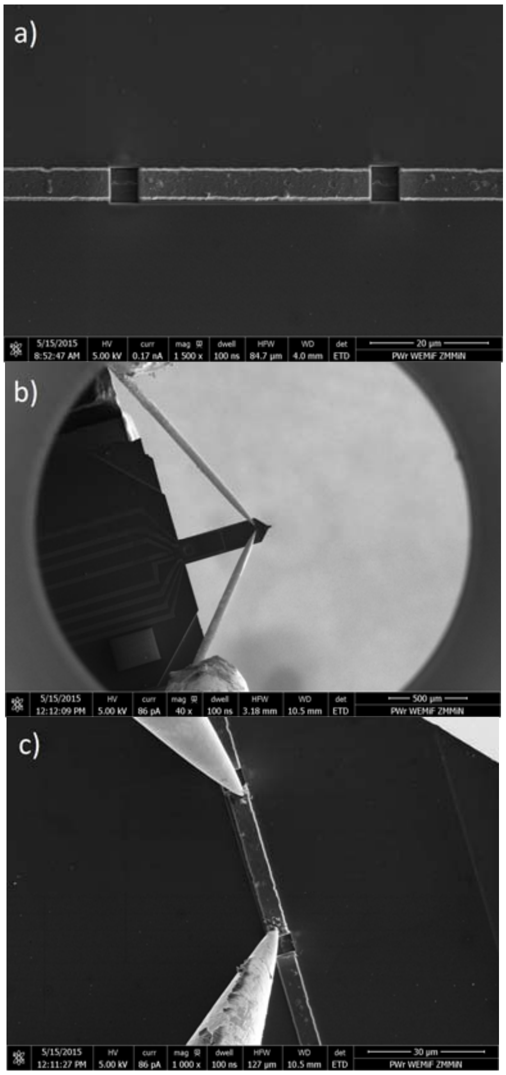


Fig. 5. Measurement of current-voltage (I/U) characteristics of the conductive path on AFM cantilever: a) prepared conductive path, b) path with probes, c) path with probes zoom in

The quality of connection was quite good, but 1 μm above it a crack of wire can be observed (Fig. 4b), that may: a) cause increase of connection resistance and b) shorten the lifetime of connection. The probable reason of this failure is incorrect setting of bonding machine that needs correction. After the processes mentioned above the wire connection in question still works properly. As opposite to classic wire testing methods only a small part of it has been destroyed.

Electrical measurements of MEMS/NEMS devices with bounded connections, as opposed to not bounded structures, are easy and do not pose major problems. However, to carry out the measurements in question, the precision electrical probes are needed. The good way to do it, is the use of micromanipulators with electrical probes and optical microscope. Sometimes the magnification of the microscope may be insufficient. Also a short focal length may prevent this kind of experiment, because of lack of space for probes between the objective and sample. To get around these limitations, we have conducted the I/U measurements of electrical path: 40 μm long and 5 μm wide, using scanning electron microscope. Figure 5 presents the considered conductive path on AFM cantilever prepared to measurements (Fig. 5a) and during measuring process (Figs. 5b,c).

In Fig. 6 the results in form of current-voltage (I/U) characteristics are shown. As can be seen the path resistance does not change in the range of 0 ÷ 130 mV, independently of current value.

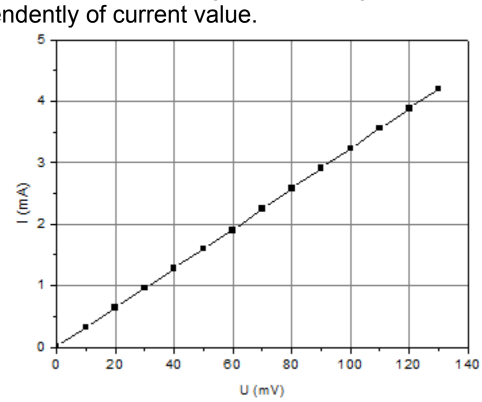


Fig.6. Results of current-voltage measurements

FIB/SEM in MEMS/NEMS fabrication: modifications and reparations

The tip of investigated cantilever after reactive ion etching (RIE) process is not good enough for high resolution AFM measurements. We used a four-step process to improve the sharpness of the tip. First two steps were rough milling (Fig. 7) in two axes to create a proper pyramidal shape and then two steps for final polishing to get sharp tip (Fig. 8).

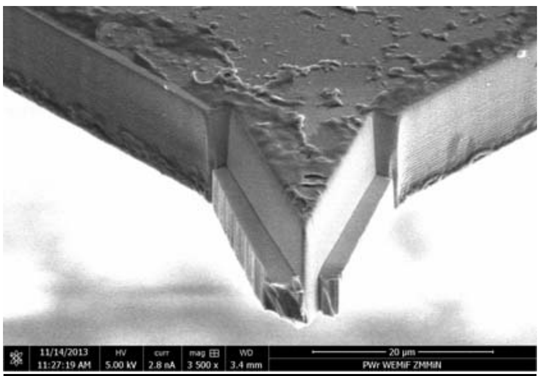


Fig.7. AFM tip during rough milling process

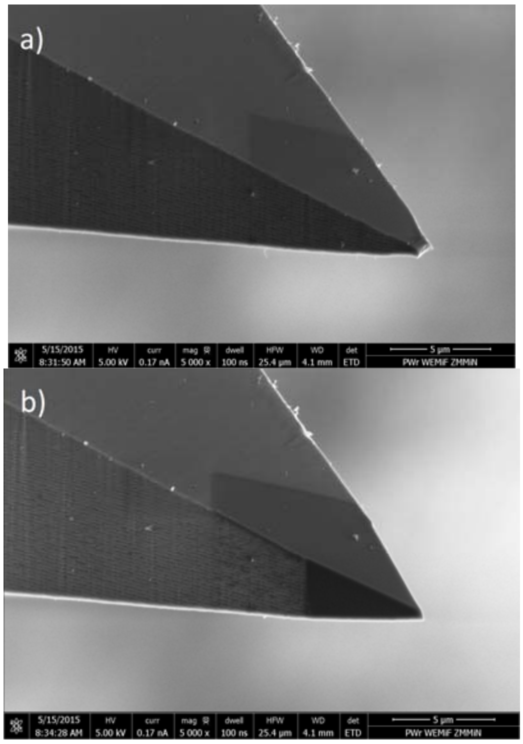


Fig.8. Sharpening of tip, a) before, and b) after the polishing process

This process is a good example of complementary of classical MEMS/NEMS fabrication and FIB/SEM technology. It shows that the fusion of MEMS/NEMS with FIB/SEM technology can allow to create devices with a new quality.

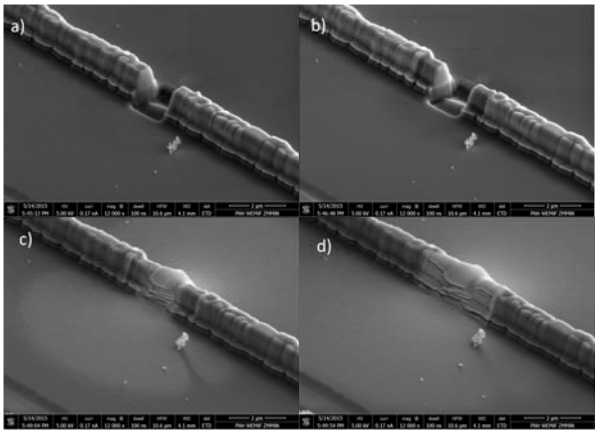


Fig.9. Three-step process for reparation of electrical gap: a) the gap, b) cleaned path, c) filled gap, d) covered filled gap

Often the failure of MEMS/NEMS is connected with the break of conductive parts of device. The simplest failure is broken electrical path. This type of destruction may give rise to resistance increase or disconnections. It also may cause too high current density or mechanical destruction. The three-step process used in our investigations for reparation of electrical gap is presented in Fig. 9. In the first step a top layer of path was removed to prepare better surface for connection (Fig. 9b). Then the gap under consideration was filled with conductive material in focused ion beam induced deposition process (Fig. 9c). After this operation the path was already conductive. In the last step filled spot and cleaned parts of path were covered with conductive layer (Fig. 9d). During this process the connection resistance decreased.

Conclusion

The aim of this short survey is to show the possibilities of application of FIB/SEM technology in MEMS/NEMS. Our experiments (only a small part is presented here) have proved that the technology in question allows to perform complex investigations and modifications of MEMS/NEMS devices and gives interesting future perspectives.

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