Michał Krysztof
Dr inż.
Wroclaw University of Science and Technology
Faculty of Electronics
Photonics and Microsystems, Department of Microsystems
michal.krysztof@pwr.edu.pl

DOI: 10.35117/A_ENG_25_07_08_03

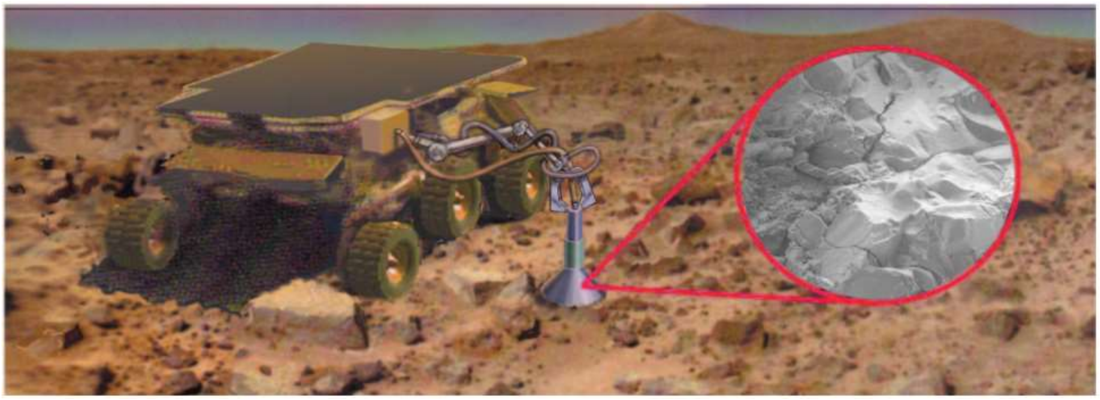
Miniature MEMS Scanning Electron Microscope

Abstract: This article presents the world's first miniature MEMS scanning electron microscope. The device, thanks to its small size, low power consumption, and durable construction, can be used in previously inaccessible places, including space missions for imaging samples of cosmic dust, lunar, or Martian soil.

Keywords: Miniature scanning electron microscope; Electron source; MEMS; Imaging

Introduction

The imaging of the surface of samples is one of the most important elements of materials research. Due to the Abbe limit, optical microscopes have a resolution limit related to the wavelength of light used for imaging (e.g., for light with a wavelength of 600 nm, the resolution of the microscope will be about 300 nm). The use of electron beam in electron microscopes allows for the observation of individual atoms, but these instruments are large and heavy. This is inconvenient, especially in space research, e.g. within the OSIRIS-REx mission [1]. Therefore, in the second decade of the 21st century, NASA began work on the miniaturization of electron microscopes, which could be used for preliminary studies of preparations obtained from the surface of the Moon [2, 3], or Mars [4]. However, the concepts presented by NASA (Fig. **1**) were not implemented.



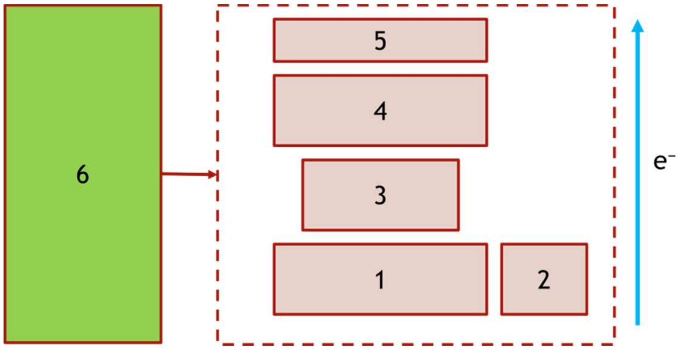
1. Visualization of the rover on the surface of Mars equipped with a miniature variable pressure scanning electron microscope (MVP-SEM) [4]

This state of affairs was identified by the author, who in 2014 began work aimed at developing a fully mobile, autonomous miniature scanning electron microscope (MEMS SEM). This article presents the results of this work.

MEMS SEM concept

According to the concept of the author [5], the subminiature scanning electron microscope is made as a MEMS structure and contains (Fig. **2**): an electron source (1), a vacuum micropump

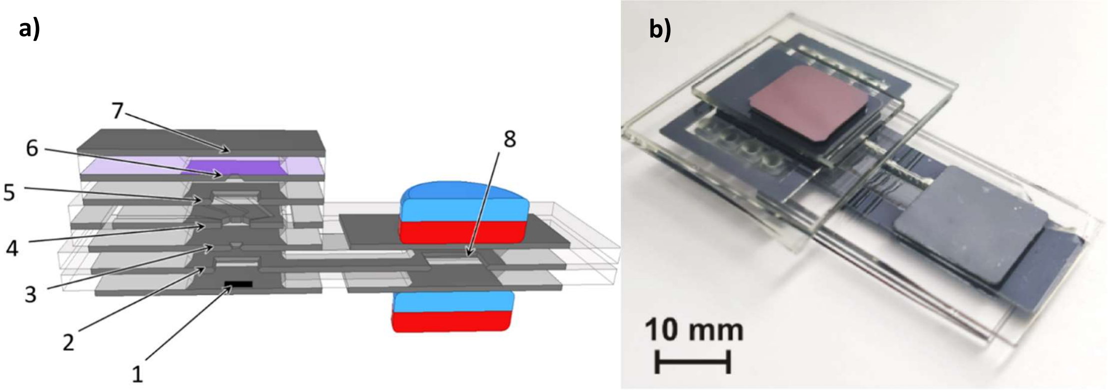
(2), an electron-optical column (3), an object chamber (4) and detectors (5). A dedicated electronic system (6) was designed for this purpose. As mentioned above, all MEMS SEM elements were made using MEMS technology from silicon and glass. The use of these materials allowed the use of anodic bonding [6] for their vacuum-tight connection. According to the concept of the author, an electron beam with energy <5keV is emitted from the cathode (1) inside the silicon-glass structure and then focused to a small size and scanned over the sample (4) using an appropriate electrode system (3). A set of dedicated detectors (5) collects electron signals, from which the surface of the sample is reconstructed.



2. Block diagram of MEMS SEM

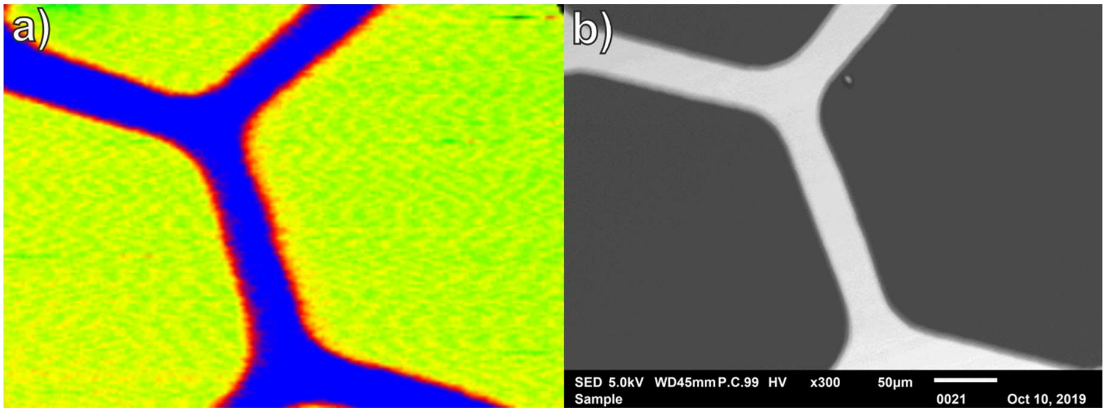
MEMS SEM implementation

As mentioned above, since 2014, work has been underway on the development of individual MEMS SEM elements and their integration into a single system [7–12]. The most advantageous emitter enabling the production of an electron beam with the smallest cross-section turned out to be a silicon emitter made using the laser ablation technique [13]. Such an emitter is characterized by a small tip diameter of < 100 nm and a very stable operation of the emitter made of p-type silicon. An electrostatic lens, which has square holes produced by wet anisotropic silicon etching, can reduce the initial spot size of the electron beam by 3.5 times [9]. The scanning system using a silicon octupole has a scanning step of 27 nm (for an electron beam energy of 4 keV and a working distance of 1 mm) [10]. The test results of individual MEMS SEM elements lead to an estimate of the resolution of the developed device at 50 nm. The completion of the work on the above-mentioned elements enabled the realization of the microscope on a chip according to the implementation diagram shown in Figure **3a**.



3. Miniature MEMS scanning electron microscope: a) scheme: 1 – silicon cathode with carbon nanotube emitter, 2 – extraction electrode, 3 – focusing aperture, 4 – octupole, 5 – backscattered electron detector, 6 – anode with silicon nitride membrane (absorbed electron detector), 7 – transmitted electron detector, 8 – vacuum micropump; b) finished device

The key point in the construction of MEMS SEM is the tight closure of the device chip. This is possible after the tight connection of silicon and glass components using anodic bonding [6]. Such a connection is durable and vacuum-tight, which makes it impossible to place the sample inside the microscope, as is the case in classical solutions. In the solution presented here, a 100 nm thick silicon nitride membrane was used, which allows maintaining a high vacuum within the MEMS SEM, while allowing the transmission of electrons outside the microsystem to the sample, which will be placed on the membrane. The MEMS sub-miniature ion sorption vacuum micropump [14], which is attached to the microcolumn from the side, is responsible for generating and maintaining a high vacuum in the MEMS SEM. The pump generates a vacuum of 10^{-5} mbar. The electron signal is detected by 3 detectors in the form of silicon collectors collecting the signal of transmitted, backscattered, and absorbed electrons on the sample [11]. For silicon electrodes, the images obtained using them do not differ significantly in quality from images obtained using a classic scanning electron microscope JEOL JSM IT-100 (Fig. **4**).



4. Metal mesh images obtained using: a) MEMS SEM, b) JEOL JSM IT-100

Summary

The world's first model of a miniature MEMS scanning electron microscope equipped with a vacuum micropump was presented. Based on the experimental results obtained, the postulated resolution of the designed device was estimated at 50 nm. Such a resolution fully enables the use of such a device for rapid analysis of dust, including cosmic dust, e.g., lunar regolith or Martian soil. Such an application is possible due to additional features of MEMS SEM, i.e. the device is small, very light and mechanically durable, and consumes very little energy. Further work on the development of MEMS SEM will continue.

Source materials

[1] D. S. Lauretta, S. S. Balram-Knutson, E. Beshore, et al. OSIRIS-REx: Sample Return from Asteroid (101955) Bennu, Space Science Reviews 212, (2017) 925–984.

[2] J. A. Gaskin, G. A. Jerman, B. D. Ramsey, C. K. Ferguson, T. O. Abbott, S. O'Brien, D. C. Joy, K G. Thaisen, L. A. Taylor, A. R. Sampson, E. A. Rhodes, E. H. Darlington, B. J. Bussey, R. P. Harvey, and P. D. Spudis, MINIATURE SCANNING ELECTRON MICROSCOPE FOR IN-SITU PLANETARY STUDIES: ELECTRON GUN DEVELOPMENT, 40th Lunar and Planetary Science Conference (2009), March 23-27, 2009 in The Woodlands, Texas.

[3] Jessica Gaskin, Terry Abbott, Stephanie Medley, Don Gregory, Kevin Thaisen, Lawrence Taylor, Brian Ramsey, Gregory Jerman, Allen Sampson, Ralph Harvey, Miniaturized

Environmental Scanning Electron Microscope for In Situ Planetary Studies, NASA Technical Reports Server (https://ntrs.nasa.gov/citations/20100017162), March 14, 2010.
[4] Jessica A. Gaskin, Gregory Jerman, Don Gregory, Allen R. Sampson, Miniature Variable Pressure Scanning Electron Microscope for In-Situ Imaging & Chemical Analysis, 2012 IEEE Aerospace Conference, 3-10 March 2012, Big Sky, MT, USA.
[5] M. Krysztof, T. Grzebyk, A. Górecka-Drzazga, J. Dziuban, A concept of fully integrated MEMS-type electron microscope, Technical Digest of 27th International Vacuum Nanoelectronics Conference IVNC 2014: July 6-10, 2014, Engelberg, Switzerland, 77-78.
[6] J. Dziuban, Bonding in Microsystem Technology, Advanced Microelectronics series, Springer 2006, The Netherlands.
[7] M. Krysztof, Field-emission electron gun for a MEMS electron microscope, Microsystems & Nanoengineering, vol. 7, nr 1 (2021) art. 43, s. 1-9.
[8] M. Krysztof, T. Grzebyk, A. Górecka-Drzazga, K. Adamski, J. Dziuban, Electron optics column for a new MEMS-type transmission electron microscope, Bulletin of the Polish Academy of Sciences. Technical Sciences 66 (2018) 133-137.
[9] M. Krysztof, Design of an Einzel lens with square cross-section, Electronics, 10, nr 19 (2021) art. 2338. s. 1-15.
[10] M. Krysztof, M. Białas, P. Szyszka, T. Grzebyk, A. Górecka-Drzazga, Fabrication and characterization of a miniaturized octupole deflection system for the MEMS electron microscope, Ultramicroscopy, vol. 225 (2021) art. 113288, s. 1-8.
[11] M. Białas, T. Grzebyk, M. Krysztof, A. Gorecka-Drzazga, Signal detection and imaging methods for MEMS electron microscope, Ultramicroscopy, 244 (2023) 113653.
[12] M. Krysztof, T. Grzebyk, P. Szyszka, K. Laszczyk, A. Górecka-Drzazga, J. Dziuban, Technology and parameters of thin membrane-anode for MEMS transmission electron microscope, Journal of Vacuum Science and Technology B, 36 (2018) 02C107.
[13] M. Krysztof, P. Miera, P. Urbański, T. Grzebyk, M. Hausladen, R. Schreiner, Integrated silicon electron source for high vacuum microelectromechanical system devices, Journal of Vacuum Science and Technology B, 42, (2024) 023001.
[14] T. Grzebyk, A. Górecka-Drzazga, J. Dziuban, Glow-discharge ion-sorption micropump for vacuum MEMS, Sensors and Actuators A: Physical, 208 (2014) pp. 113-119.