

Jan A. Dziuban

Prof. dr hab. inż.

Space Research Centre

Faculty of Electronics, Photonics and

Microsystems

jan.dziuban@pwr.edu.pl

DOI: 10.35117/A_ENG_25_07_08_01

Space MEMS and instruments – a review of results of mother author’s institution

Abstract: The review of space applications of MEMS sensors as well as the first presentation of plasma fluid optical gas microspectrometer and ion mass microspectrometer, developed in Poland for future Venusian, Martian and Lunar missions have been presented. Additionally, Polish subminiature biomedical lab-on-chip payload and its space tests at LOE has been showed. Finally CSAC atomic microclock and its applications has been discussed.

Keywords: MEMS; Space; Miniaturization; Spectrometer; Lab-chip; CSAC

Introduction

The rapid growth of application of miniature space ships including micro and nanosatellites able to penetrate deep space has involved significant reduction of space mission costs. The rapid growth of nanosatellite business has been as well accelerated by easy access to low-power, radiation resistant cheap microprocessors, high-efficient solar panels, and miniaturized equipment especially developed for nanosatellite use. Among other, one of the most significant barrier blocking nanosatellite missions is lack of miniature instruments. The actually applied in large space ships are noncompatible with nanosatellite specify [1]. This is as well significant obstacle in realization of a new, planned space missions of NASA and ESA, to be realized by small robot-scout, where array of movable scouts equipped with set of miniaturized instrument will penetrate Martian or Lunar surface, gas, or liquid or aerosol atmospheres. Some of the missions will apply impact landing, so, robo-scout with miniature instrument must survive minimum 1500 G of deceleration. Taking all of this into account it becomes clear why new miniaturized instruments are becoming important, but must be developed “from the beginning”.

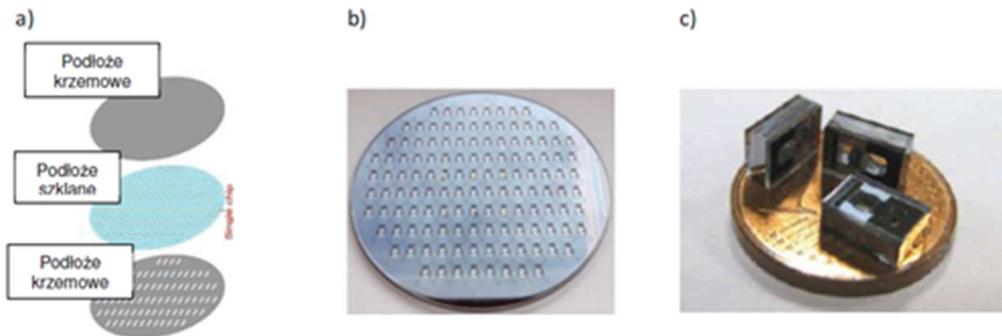
MEMS specific

Miniaturization of instrumentation for space applications is an area of microsystem MEMS technology. Great success of MEMS (micro-electro-mechanical system), being actually produced in billions pcs a year and widely applied at Earth, with niche market comparable to semiconductors comes from excellent mechanical and electrical (electronics) properties of silicon and compatible materials; its microelectronic origin and low price. MEMS is small, light, stable and compatible with silicon electronics.

As commonly known, MEMS consists of 3D micromechanical parts integrated on-chip with planar microelectronics. Parts co-work in system. Not jumping into the details, the technology of MEMS utilizes adapted from microelectronics procedures (photolithographic patterning, deposition and removing of thin-film layers, doping, metallization) supported by so called wet/dry deep and surface micromachining, and bonding. 3 to 8 “silicon/glass substrates are usually processed, sandwiched multi-substrate is usually obtained by anodic bonding of silicon and glass. Following to that, substrates are sewed into chips (Fig. 1). More about MEMS in [2] for example.

Early Space Sensor MEMS

Silicon pressure sensors as well as accelerometers – primitive MEMS devices - were applied in early space manned American missions in 60's of the past century. Today, MEMS are applied widely, pressure and acceleration sensors as well as gyro, vibrato-meters, sun-trucker, bolometers etc. A review of space MEMS is given in [3].



1. MEMS technological principle; a) silicon/glass/silicon micromachined substrate prior to bonding; b) silicon/glass sandwich; c) several MEMS chips (cesium optical cells of atomic microclock are shown at 10 EURcent coin)

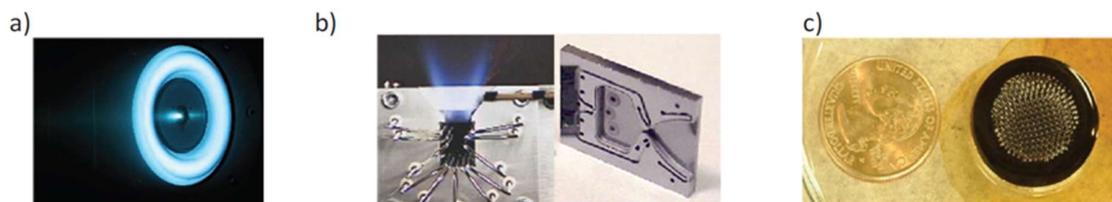
Space MEMS actuators

Micro-propellers are among significant group of space actuators. First jet engine based on decompression of high-pressure Argon and precise steering of injections of portions of gas. This subminiature propeller has been made in a form of multilayer all-silicon structure [4].

The ion thruster [5] (Fig. 2 a) utilizes matrix of subminiature 3D micromachined vias with high-voltage thin film electrodes. Liquid Gallium flows through particular hole where is ionized and accelerated by an electric field. High-speed ions jets induce low force moving the nanosatellite, but thanks to their very high speed may push it to extremely high final velocity.

The rocket MEMS engine [6] consists of several deeply micromachined and fusion bonded silicon substrates. Methyl spirit and liquid oxygen are injected and react chemically inside the combustable chamber (well seen at Fig. 2b) reaction gaseous products form the jet propelling a nanosatellite. A post-stamp size propeller generates 1 Nm thrust with thrust-to-weight proportion 1000:1.

Arrayed MEMS blaster [7] (Fig. 2c) consists of several wet deeply etched in silicon reversed pyramids covered with thin silica membranes (1000nm-thick). At the surface of each membrane a thin-film resistor is formed. Pyramids are filled up with blasting polymer. Current impulses (a few mA) heats the resistor to circa 800 degC inducing rapid chemical reaction destructing membranes and resistor but generating strong impulse of momentum.



2. MEMS space micro propellers; a) working ion thruster, b) rocket MEMS, c) blasting arrayed engine

MEMS Analytical instruments

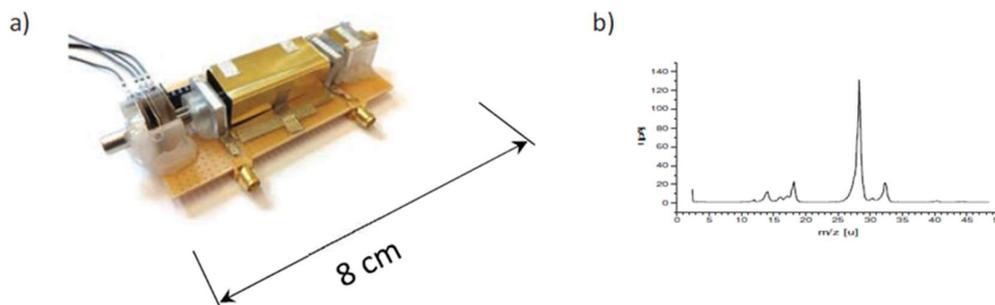
As mentioned earlier, development of subminiature space-applied analytical instruments. First works on the integrated gas chromatograph for analysis of Titan atmosphere started in 1976 (!) [8]. Works of Stanford's diploma students did not give result, but, continued by inventors have finished by almost 25 years. The GMC Agilent 2000 instrument (with MEMS injector and TCD catharometer) has been applied at ISS. New construction has been proposed by MDL (micro-device laboratory) of JPL [9].

Gas chromatographs are not ideal gas mixture analyzers. Analytical properties of instruments are dictated by a chromatographic columns what is more, they cannot work in vacuum. Unknown and low-pressure gaseous mixtures – according to the state of an art -are easily analyzed by ion mass spectrometers, but there is a lack of miniaturized instruments.

MEMS ion mass spectrometer (MS-MEMS)

Works based on precise mechanics technology on development of small ion mass spectrometers has been continued for years in plenty of institutions [10]. Some of the developed instruments have been applied in the space missions being realized by large space ships and landers (Comet Interceptor or Perseverance Rover), but they are still too big to meet nanosatellite specifications. ESA and NASA needs subminiature analyzers, with mass below 500g, mechanical robustness 50 G/1500 Hz (in future 1500 G for impact landers). Analyzer has to work in wide range of gas mixture pressure (kPa to microPa). In 2021 ESA announced call [11] on the invention of MEMS ion mass spectrometer for future space missions. This instrument has been realized by our group, chosen by ESA on a base of our heritage (works on gas analyzers started two decades ago and we dispose full MEMS line as the only academia in Poland).

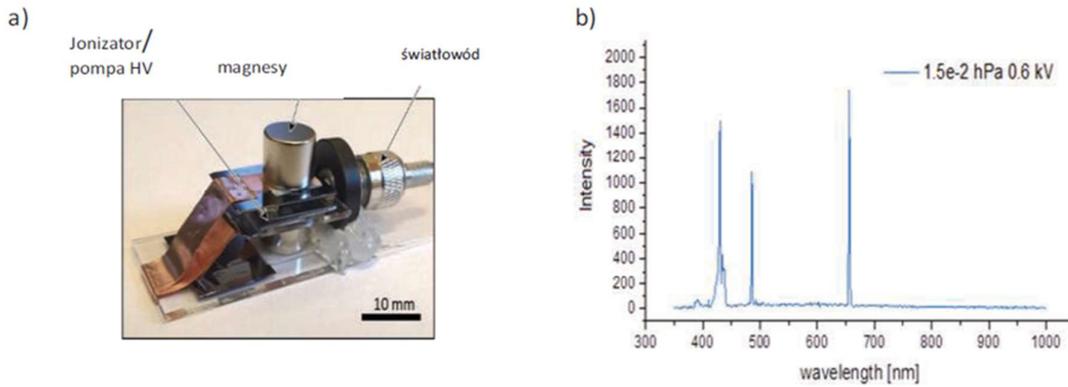
In our MS-MEMS (Fig. 3) analytical sample is ionized inside a MEMS ionizer and is injected into MEMS ions separator. After separation of ions (by mass to charge factor m/z) they enter quadrupole MEMS detector. High vacuum inside the MS-MEMS is maintained by high vacuum own micro MEMS pump. More detailed description of the MS-MEMS subminiature instrument is given in article of T. Grzebyk i P. Szyszka presented in this paper.



3 Subminiature ion mass spectrometer; a) preliminary version at a glance, b) spectrogram of air

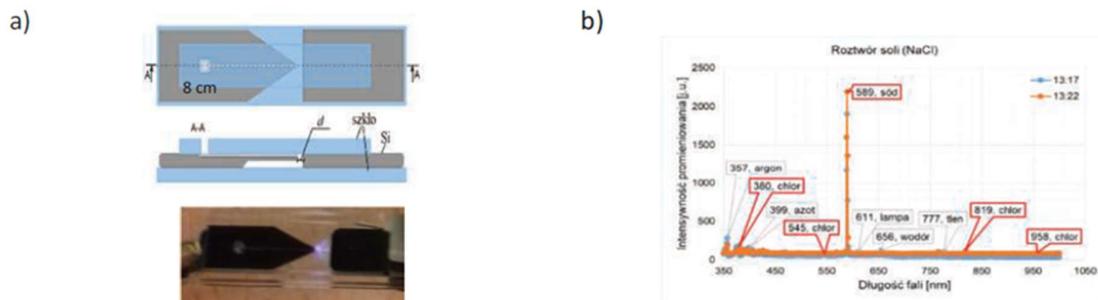
MEMS plasma spectrometer

We have developed chip-scale plasma ions spectrometer with optical signals detection. Analytical gaseous sample is ionized inside MEMS magnetron ionizer, playing in parallel functions of high vacuum micro pump. Excited ions form glowing plasma, light generated by plasma is analyzed by MEMS optical spectrometer. Each of excited gas component emits characteristic light pike, what allow to identify its nature. Application study made by us together with partners from JPL NASA/Caltech shows potential of the instrument as analyzer of Martian atmosphere including biotic/abiotic Methane detection [13].



4. MEMS plasma spectrometer; a) ionizer with fiber optic, b) Methane spectrogram

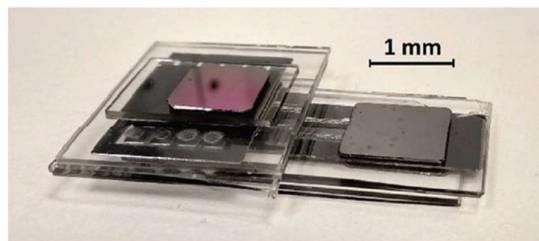
In version of this instrument liquid or aerosol sample is delivered by microcapillary to electrospray jet ionizer. Driven by high electric field sample is ionized by field emitted electrons, glowing plasma jet is formed. Light emitted by plasma is analyzed giving optical spectrogram of emission. Preliminary studies done with partners from MIT [14] have shown usability of the instrument in future Venusian parachute/balloon missions.



5. Fluids/aerosols plasma spectrometer; a) cross section and working jet-spray chip, b) spectrogram of salted water aerosol

Transmittive chip-scale electron MEMS microscope – TEM MEMS

Almost two decades ago NASA announced a need for subminiature electron microscope to be applied as visualization instrument overcrossing limits of classic optic microscopes. Works on chip-scale transmittive microscope integrated on chip being realized by our group are based onto our intensive activity in the field of nanoelectronics (more about in proceedings of International Vacuum nanoelectronic Conferences 2012-2024). The TEM MEMS is more detailedly described in article of M.Kryzstof presented in this paper. Here the chip of preliminary version of the instrument is shown (Fig. 6).



6. Completed TEM MEMS on-chip, at left electrono-optical column and at right High Vacuum MEMS micropump are shown

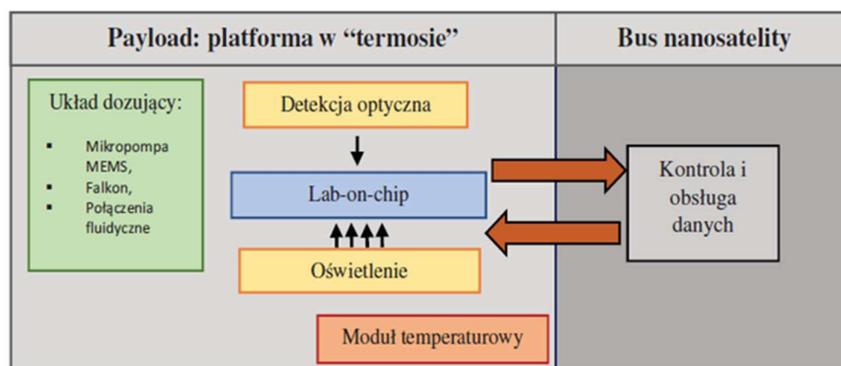
Space lab-med lab-chip laboratory

Life in microgravity has been investigated from the very beginning of space missions. Today, majority of life-oriented scientific investigations are done at International Space Station ISS, but growing number of astro-biomedical experiments at nanosatellites is being observed actually. Chosen examples of them are shown in the Table 1.

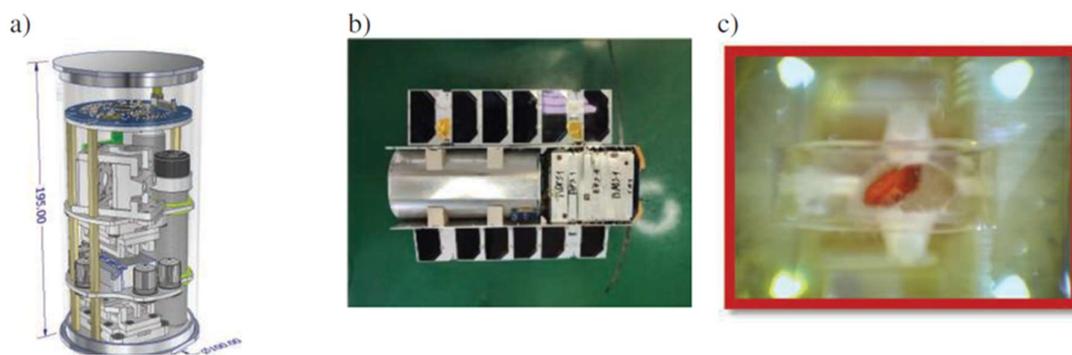
Tab. 1. Bio-nanosatellite missions

	GeneSat-1	PharmaSat	O/OREOS		SporeSat	EcAMSat	Biosentinel
Confiration of nanosatellite	2U payload, 1U bus (6,8 kg)	2U payload, 1U bus (5,5 kg)	2 x 1U payload, 1U bus (5,5 kg)		2U payload, 1U bus (5,5 kg)	3U payload, 3U bus (14 kg)	4U payload, 2U bus (14 kg)
Experiment	<i>E. coli</i> Gen expression	<i>S. cerevisiae</i> Drug resistance	Biological potential of <i>B. Subtilis</i> and <i>H. Chaoviator is</i>	Degradation of PAH, amino acid, porphyrin, quinone	Influence of microgravity onto plants seeds	<i>E. coli</i> Drug resistance	Badania mutacji DNA <i>S. cerevisiae</i>
Detection method	Fluorescence of GFP	Optical absorbance	Colorometry	UV-VIS spectroscopy	Conductance	Colorometry	Colorometry
Launching year	2006	2009	2010		2014	2017	2022

Proudly inform, that we have created and successfully tested in space a nanosatellite (made by Sat-Revolution Ltd equipped with lab-chip payload [15, 16] with double automatic subminiature laboratory (1,5 U, circa 1,3 kg). The schema of the laboratory is shown in the Fig. 7. Its schematic view, nanosatellite and germinating at 500 LEO seed in Fig. 8. More in articles of P. Sniadek and A. Podwin presented in this paper.



7. Simplified schema of laboratory for space experiments



8. The nanosatellite bio-laboratory; a) payload schematically, b) completed nanosatellite with the payload, c) seed germinating at ~500 km LEO

MEMS Atomic microclock

Works on optical chip-scale cesium atomic microclock CSAC (1ccm, 30 g, 100 mW) started at the beginning of XXI Century in USA (DARPA financed) and in EU (MAC-TFC financed by European Commission). There have been reported CSAC developed in Russia, China, Israel [18]. Our team has been deeply engaged in the invention of European microclock and is active in the subject actually. Block schema, optical cesium cell and first physical package of European microclock are shown in the Fig. 9.



9. MEMS atomic microclock; a) schema, b) cesium optical cell, c) Mark IV primitive but working physical package of the European microclock (credit of dr .P. Dziuban, actually CTO Creotech Instruments SA, Warsaw, Poland

The principle of work of CSAC is simple. VCEL 852 nm laser light is FM modulated ± 4.6 GHz. The light is absorbed inside cesium optical MEMS cell. If doubled frequency of modulation equals $9,192\,631\,770\text{ Hz} \pm 0,1\text{ Hz}$, the absorption of light is higher, so dark current in the pin detector becomes smaller. Modulator/VCEL / pin work in a loop to keep dark current at smallest level. Then, a frequency of the local generator corresponds to $9,192\,631\,770\text{ Hz} \pm 0,1\text{ Hz}$.

Rubidium and cesium atomic microclocks are produced by 3 or 4 companies in USA, Israel and (?) China, but are not offered at free market. This is critical component military applied. Report of the European Commission [18] clearly indicates that lack of an European microclock limits further on development of European space, warfare and digital industries.

More about microclock in article of P. Knapkiewicz presented in this paper.

Summary

The family of subminiature instruments for space applications, developed by our team invented in the period of last five years is founded on over three decades of scientific research financed from different domestic and foreign In the Kingdom of High and Critical Technologies nothing is going fast, cheap and good. Actually we dispose instruments at different TRLs. We would like to applicate our instruments in Polish Space Programs organized under auspicious of POLSA the Polish Space Agency. In our opinion miniaturization of space instruments and mechanical equipment could be our national space specialization. Space microgravitational bio-medical experiments made with use of miniature laboratories should as well become our national specialization. We strongly recommend to establish polish national atomic microclock program. Finally, we would like once again to propose Polish Martian mission realized by two-three nano-space ships (nanosatellites) with polish original scientific apparatus. This cheap deep-space mission is realistic as shown in the Mars mission facility report [23].

Source materials

- [1] Ch. Cappelletti et al., CubeSat Handbook – from Mission Design to Operations, Academic Press, 2021
- [2] J. A. Dziuban, Bonding in Microsystem Technology, Springer, 2007
- [3] James J. Allen, MEMS and microstructures in Aerospace Application, CRC Press 2017
- [4] Y. Backlund, K. Hjort, S. Johansson, L. Stenmark, Micro Sculpturing: Somewhat new materials and micromachining methods to meet new applications, Proceed. Eurosensors XIII, 13th European Conf. On Solid-St. Transducers, den Haag, Holland, September 12–15, 1999
- [5] M. Tajmar, P. Laufer, and D. Bock Chip based MEMS Ion Thruster to significantly enhance Cold Gas Thruster Lifetime for LISA Journal of Physics: Conference Series, Volume 840, 11th International LISA Symposium 5–9 September 2016
- [6] London, A. Epstein, A. Ayon, S.M. Spearing, T. Harrison, J. Kerrebrock, A microfabricated high pressure bipropellant rocket engine, Book of Abstracts Eurosensors XIV, 14th European Conf. On Solid- St. Transducers , Copenhagen, Denmark, August 28–30, 2000.
- [7] H. Espinoza, Microrockets, MEMS lecture, MIT, ME381, 2006
- [8] S.C. Terry, J.H. Jerman, J.B. Angell A gas chromatographic air analyser fabricated on a silicon wafer, IEEE Trans. Electron Dev. vol. 26 issue 12, 1979
- [9] M. Darrach, Next Generation Gas Chromatograph Mass Spectrometers, MDL report, JPL number CI 19-2467, 2022
- [10] D. T. Snyder, Ch. J. Pulliam, Zheng Ouyang, R. G. Cooks Miniature and Fieldable Mass Spectrometers: Recent Advances Anal. Chem. Oct 21;88(1),2–29, 2015
- [11] 1-9847 MEMS based mass spectrometry – expro; MEMS-based mass spectrometry for space applications, ESA call, 2021
- [12] https://www.esa.int/Space_Safety/Space_Weather_Projects_and_Core_Activities
- [13] J.A. Dziuban, P.Knapkiewicz, T.Grzebyk, Pin Chen, MEMS ion optical spectrometer for methane detection on Mars, Proceedings of Power MEMS Conference, Salt Lake City , Utah, USA, 2022
- [14] W. Buchanan R. Agrawal, J. Longuski, S. Saikia; VLF Descent Probe Breakdown, Purdue Univ. 2020
- [15] Project no: POIR.04.01.01-00- 0010/19 entitled “Bio nanosatellite using miniaturized lab-on-chip instruments and methodology of conducting biomedical research with its use in microgravity”, financed by NCBiR
- [16] A.Krakos (Podwin), W. Kubicki, P. Śniadek, A. Graja, M. Białas, D. Przystupski M. Psurski, M. Jurgad, R. Walczak, J. Dziuban, Lab-on-chip platforms for space biology applications 73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.
- [17] P. Śniadek, B. Kawa, A. Graja, A. Krakos, W. Kubicki, R. Walczak, J. Dziuban Lab-payload for biological CubeSat Satellite, 73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022
- [18] M. Travagnin, JRC technical report Chip-scale atomic clock; physics, technology and applications, ISBN 978-92-76-40666-2, 2021
- [19] P. Knapkiewicz, J. Dziuban, R. Walczak, L. Mauri, P. Dziuban, Ch. Gorecki, D. Miletic, Ch. Affolderbach, G.Mileti. MEMS Caesium Vapour Cell for European Micro-Atomic-Clock, S&A, 2009
- [20] Grimm, D., Recent Advances in Thyroid Cancer Research, Int. J. Mol. Sci., vol. 23, 4631, 2022
- [21] J. A. Dziuban A Podwin, P. Śniadek, A. Graja Dr D. Przystupski, A. Gorska, O Michel, J. Saczko, J. Kulback, Universal lab-on-chip-based autonomous 2 U payload for culturing

and dynamic evaluation of cancer cell in microgravity, Cancer World Congress,
Budapest, 2024