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Vacuum microdevices

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Abstract. In the paper MEMS-type microsystems working in vacuum conditions are described. All the benefits and drawbacks of vacuum generated in microcavities are discussed. Different methods are used to produce vacuum in microcavity of MEMS. Some bonding techniques, sacrificial layer method or getter materials are presented. It is concluded that the best solution would be to invent some kind of vacuum micropump integrated with MEMS structure. Few types of already existing vacuum micropumps are shown, but they are not able to generate high vacuum. As the most promising candidate for miniaturization an orbitron pump was selected. The working principle and novel concepts of its construction are described. The most important part of the micropump, used for gas ionization, is a field-emission electron source. Results of a research on a lateral electron source with gold emissive layer for integration with a micropump are presented.

Key words: vacuum microsystems, miniature vacuum pump, field-emission electron source, MEMS.

1. Vacuum MEMS

Microsystems are microdevices consisting of sensors or/and actuators assisted with electronic circuits, which steer their work and deal with data processing. Depending on specific construction and application one can meet in literature many different names for those systems: MEMS (Micro-Electro-Mechanical Systems), MOEMS (Micro-Opto-Electro-Mechanical Systems) and μTAS (microTotal Analysis Systems). Microsystems are fabricated using microelectronic and microengineering technologies. Typical microdevices have planar sizes in the range of millimeters or centimeters, but at least one of their dimensions is about a few micrometers.

MEMS-, MEOMS- or μTAS-type miniature devices have found wide applications in many areas of our life: in science, motor industry, avionics, chemistry, pharmaceutics, and telecommunication and even in household products – mostly as intelligent sensors and actuators.

MEMS like accelerometers, gyroscopes, RF switchers, high frequency filters and absolute pressure sensors, based on resonating microstructures, require vacuum for stabile and long-lasting operation (Fig. 1) [1–2]. Microswitchers require vacuum on level of about 1000 Pa, but for example high class pressure sensors and gyroscopes need pressures lower then 10^{-2} Pa in operating cavity, and very sensitive IR sensors work properly in pressure range from 10^{-4} to 10^{-3} Pa. Presence of gas particles influence vibrations of such microelements as miniature diaphragms, springs or cantilevers, decreasing their sensitivity and changing operating frequency. Ultra high vacuum is necessary in microdevices like field-emission electron sources, electron microscopes, and mass spectrometers [3]. In these devices sufficiently long free path of electrons or ions is a critical parameter. It should be longer then inter-electrode distance. Moreover, residual gases remaining in vacuum microchamber change the parameters of electron emission (different work function, reverse ion bombardment of cathode).

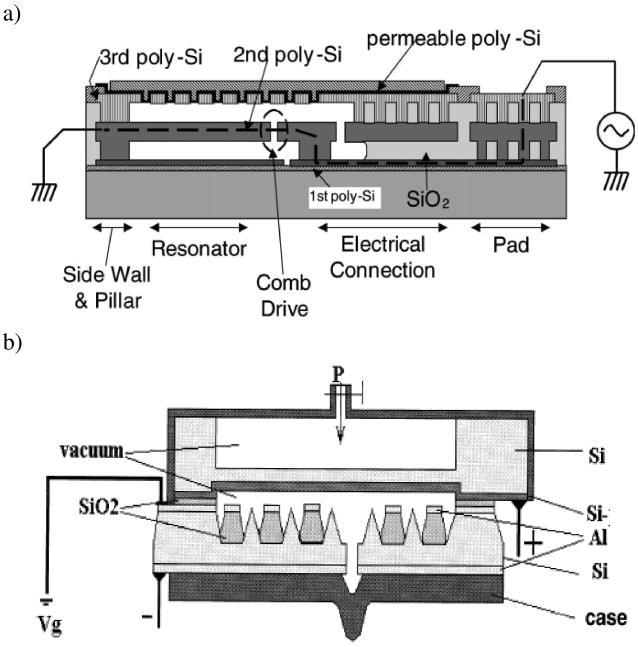

Fig. 1. Examples of MEMS working in vacuum conditions: a) gyroscope after Ref. 2, b) pressure sensor with field microemitters after Ref. 3

Vacuum encapsulation of MEMS is the most important step of the fabrication process. It often determinates the cost of a complete microsystem and delays a transfer from a laboratory prototype to a commercial implementation.

In macro device, which operating chamber has volume of several liters, vacuum can be generated by use of the commercial vacuum pumps, which can evacuate both air and chemi-

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cally reactive gasses. There is no problem with reaching the pressure level of 10^{-6} Pa. The situation looks totally different in case of microcavities. Because of a very small volume (several milliliters or less) typical pump system cannot be applied. Despite technical problems, also some additional difficulties have to be considered. They appear due to very high surface/volume ratio. Some surface phenomena start to play a dominate role. Additionally, different gas particles as well as moisture diffuse into MEMS microcavity through microchannels and microcracks in bonding area or in microchamber walls. Moisture is the most deadly factor, because it may condense on moving elements of MEMS and cause their damage (sticking, braking, cracking, corrosion) [4]. To sum up, a few phenomena could be listed, which make it hard or even impossible to achieve high/ultra high vacuum in microcavity:

- gas desorption from microcavity surface,
- gas penetration through imperfections of bonding area,
- gas penetration through microdefects of material structure,
- outgasing during bonding process and working of a microdevice,
- diffusion through organic materials.

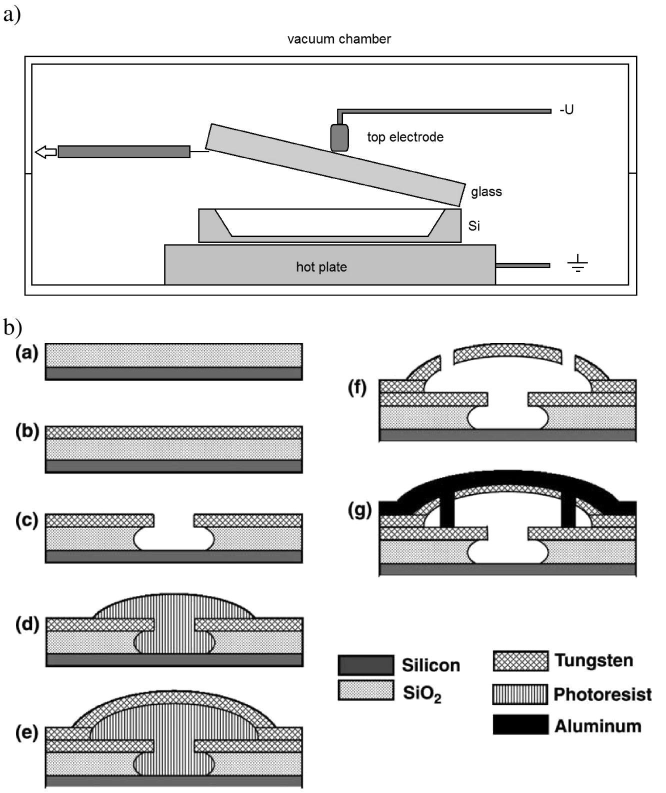

Fig. 2. Vacuum MEMS fabrication: a) with using vacuum anodic bonding process, b) with using sacrificial layer technique after Ref. 5

MEMS-type vacuum microsystems are currently fabricated by use of the different bonding and encapsulation techniques. Most often two main parts of microsystem (properly formed glass and/or silicon wafers) are connected in wafer-to-wafer bonding process (Fig. 2a). Some different types of those processes can be applied: low- or high temperature bonding with using connecting metal or glass layer (eutectic bonding and glass-frit bonding), and with using electric field applied to the bonded structure (anodic bonding). In practice it is hard to achieve pressure lower than 10 Pa. Bonding process which is held in elevated temperature leads to final pressure in microcavity at level a few orders of magnitude higher than that, which is generated during encapsulation process.

Vacuum in microsystems can be obtained also by use of the sacrificial layer technique (Fig. 2b) [5]. Whole structure is fabricated on one substrate; movable elements and microcavity what is filled with sacrificial layer. The last stage of fabrication process rests on releasing suspended parts by removing unneeded sacrificial layer. This process and final covering with metallic or semiconductor layer has to be carried out in vacuum.

With time the pressure in MEMS microvolume deteriorates, thus maintaining stabile vacuum conditions in microsystems is a hard technical problem. A major step forward in vacuum MEMS development was the use of a getter material (Fig. 3). This is highly reactive material, which easily forms stabile chemical compounds with residual gases (H_2O, O_2, CO, CO_2, N_2 and H_2). Getters have already been used in macro-scale electronic instruments (electron lamps, kinescopes, flat displays) for years.

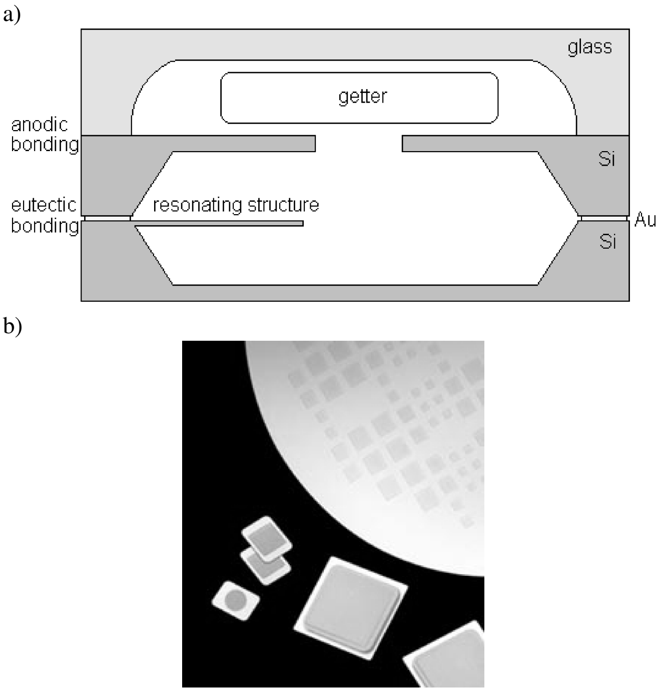

Fig. 3. Getters in MEMS structures: a) diagram of MEMS with integrated getter, b) NEG from SAES in shape of pastilles (PageLids) and thin films (Pagewafers) after Ref. 6

Recently, a new type of non-evaporable getters (NEG) specially dedicated for MEMS has been elaborated by SAES Getters, France [6]. Firstly, they were formed in pastilles and introduced into a specially prepared microchamber close to proper microcavity. This pastille was made of compressed porous powders, which were combination of metallic alloys, mostly titanium, zirconium, aluminum and barium. Nowadays, getter can be placed in the same cavity as moving microstructures in the form of thin or thick film (deposited in chemical vapor processes or printed). They can be patterned (in photolithography process) in any shape, adjusting to individual MEMS. External (pastilles or strips) getters as well as integrated getter films are passivated, their surface is inactive. They need activation to start absorbing gas particles. Most of bonding techniques: anodic, glass-frit and eutectic bonding provide conditions suitable to activate NEG getters (300–450°C, 45 min). Introducing getters into MEMS microcavity stabilizes vacuum (10^{-1} Pa) and improves radically performance of the device for many years.

In the past few years a significant progress in Vacuum Nanoelectronics has been observed. Many potential applications of miniature electron field sources in modern microdevices are being now considered. Miniature versions of the free electron microlasers for Roentgen and terahertz radiation and mass spectrometers are developed. All of them need ultra high vacuum for proper working. Lasers in macro scale have been elaborated in recent years, but their miniaturization is a dream of future. The major obstacle for faster development is lack of devices able to generate vacuum in microcavities.

2. Vacuum micropumps

It seems that the problem with generating vacuum in micro scale can be eliminated by constructing some kind of miniature vacuum pump, integrated with MEMS structure. There are only a few existing and described in literature vacuum micropumps (Fig. 4): diaphragm pump, thermal molecular pump and vapor jet pump [9]. The first one is very similar to fluid pumps, a diaphragm vibrates due to piezoelectric force, and a shape of ejector nozzles determinates the direction of a flow [7]. It could be used more for supplying chromatographs with external gases than for vacuum generation, because underpressure generated with it is only 7 kPa.

In the group of thermal molecular pumps three types of pumps can be distinguished: Knudsen pump, accommodation pump and thermomolecular pump. Only the first one has been fabricated in MEMS technology [8]. The Knudsen pump relies upon the principle of thermal transpiration. Different temperatures are applied to two microchambers connected with a narrow channel. A net gas flow from the colder chamber to the hotter chamber occurs because of the temperature dependence of molecular flux rates through a narrow tube. The serial connection of cold and hot microchambers with narrow and wide channels can decrease pressure even further. By this moment pressure only few times lower then atmospheric one has been achieved.

Third type of miniature vacuum pumps is a MEMS-type version of typical diffusion pump [9]. In presented construction vapor (nitrogen or water vapor) was applied from external source and results were even less promising then for Knudsen pump (850 mbar). Described constructions are not sufficient for the aforementioned applications, that is why one has to look for a totally different approach for producing ultra high vacuum.

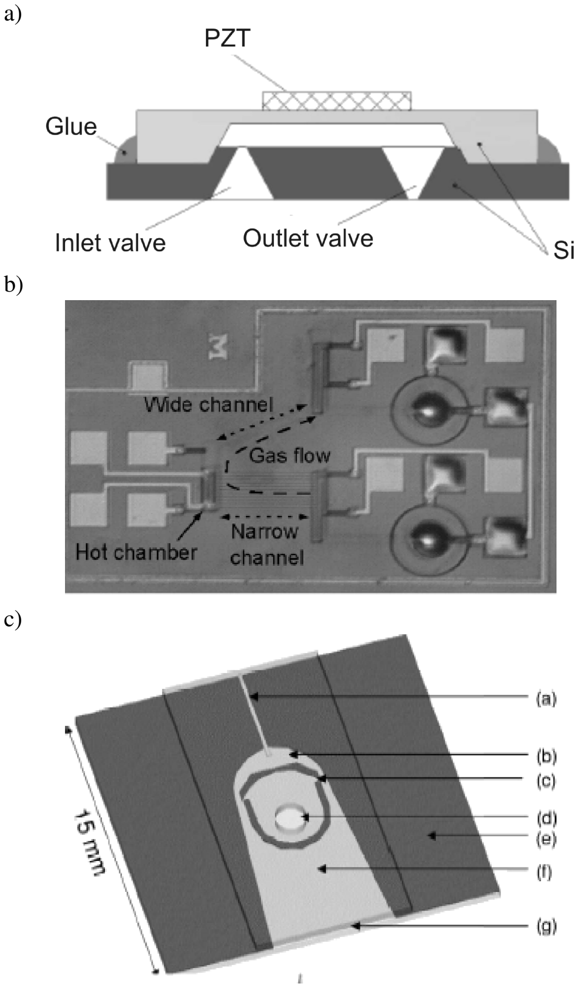

Fig. 4. Vacuum micropumps: a) diaphragm pump after Ref. 7, b) Knudsen pump after Ref. 8, c) vapor-jet pump after Ref. 9

Nowadays, to achieve high vacuum conditions in microcavities vacuum bonding techniques with integrated getters are being used. The getter material absorbs gas molecules, which incidentally encounter its surface. In macroscopic sorption pumps this process is enhanced by ionization of pumped gas. To ionize gas particles a thermocathode, which generates an electron beam, is used. Applying high negative voltage to a collector covered with the getter material results in attracting ions towards it, thus they are chemically or physically bonded. In consequence the gas particles are eliminated from the chamber and vacuum improves.

Miniaturization of ion-sorption pumps is a hard technological problem. In silicon/glass MEMS devices one cannot apply high temperatures or voltages. Electron sources using thermocathode have to be replaced. Wide research on field electron sources with low threshold voltages which can substitute conventional cathodes has been done. The second problem is ionization of the gas particles in a small cavity; the interelectrode distance is so small that the probability of electron collision with a gas particle is too small. This problem can be eliminated by increasing an electron path. This idea is used in macroscopic orbitron pump [10]. Electrons in vacuum chamber move in spiral trajectories through a positive bias applied to central anode rod.

Investigations on miniaturization of an orbitron pump have been held for years, but did not give satisfactory results (Fig. 5). Wilcox [11] presents conception with a ring-like anode instead of straight one, and Koops' proposal [12] assumes using field-emission electron sources located in a silicon/glass structure. None of those concepts have been realized in practice.

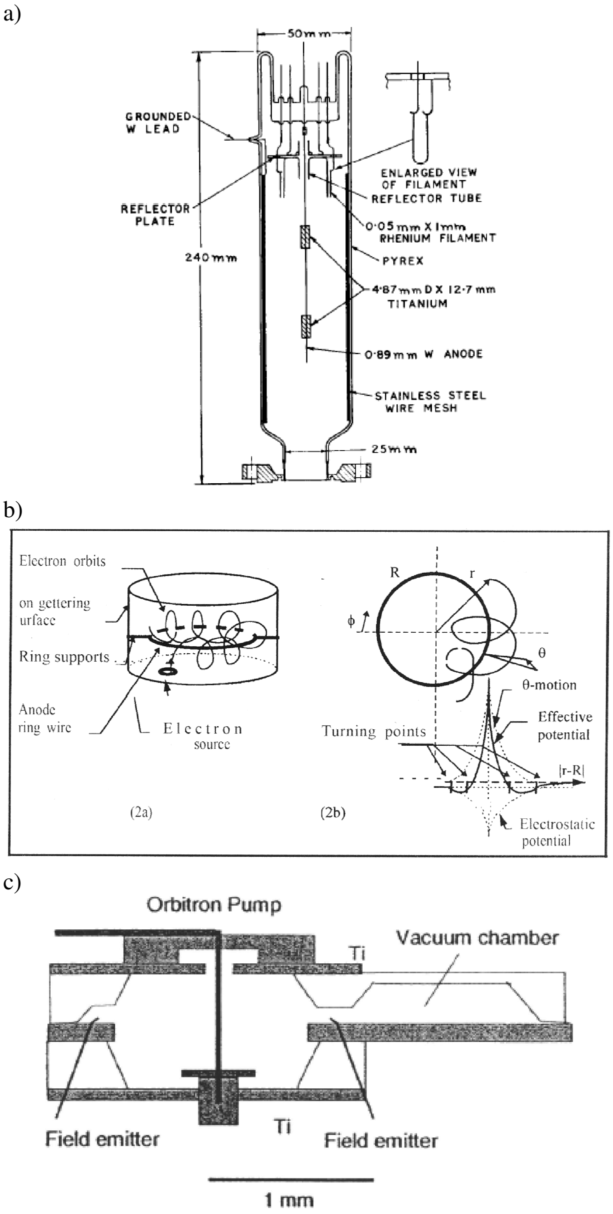

Fig. 5. Schematics of orbitron micropumps: a) first miniature version after Ref. 10, b) conception with a ring-like anode after Ref. 11, c) conception of silicon/glass MEMS-type pump after Ref. 12

3. Orbitron micropump – concept and first technological works

Taking into consideration all the restrictions connected to the microengineering techniques, a novel concept of a miniature orbitron micropump has been presented (Fig. 6). To lengthen the path of electrons (to provoke orbital movement) and increase the probability of gas ionization, introducing a high electric field induced by the central anode rod or the magnetic field (two external magnets) would be the right solutions.

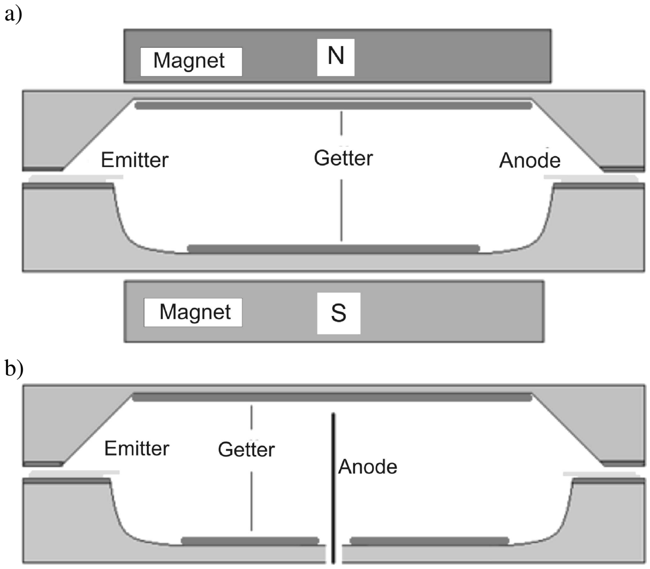

Fig. 6. Construction of orbitron micropump with use of: a) magnetic field, b) electric field

For the working microchamber of a few milliliters the magnetic field of about 0.2 T seems to be sufficient. It is a value which can be easily achieved by using neodymium magnets. In a case of the anode rod voltage of a few hundred volts has to be applied. In both conceptions getter layers would be deposited on bottom or/and top wall of the chamber. The getter biased negatively attracts positive ions and gives an effect of gas pumping.

The most important part of a pump is an electron source. This is the reason why in first step of practical implementation of the micropump concept, the lateral field emitter compatible with the whole construction was fabricated (Fig. 7). The test structure was realized on a silicon substrate of (100) crystallographic orientation. The wafer was oxidized (1 μm thick) and three metallic films were deposited chromium, nickel and gold (50/50/300 nm thick). The emitting nanotips were formed in the photolithography process. The distances between electrodes were from 20 μm to 2 mm. All measured structures showed good emission properties (threshold voltage was about 15 V, current reached miliampers, electrical field enhancement factor was about 10^8 cm^{-1}).

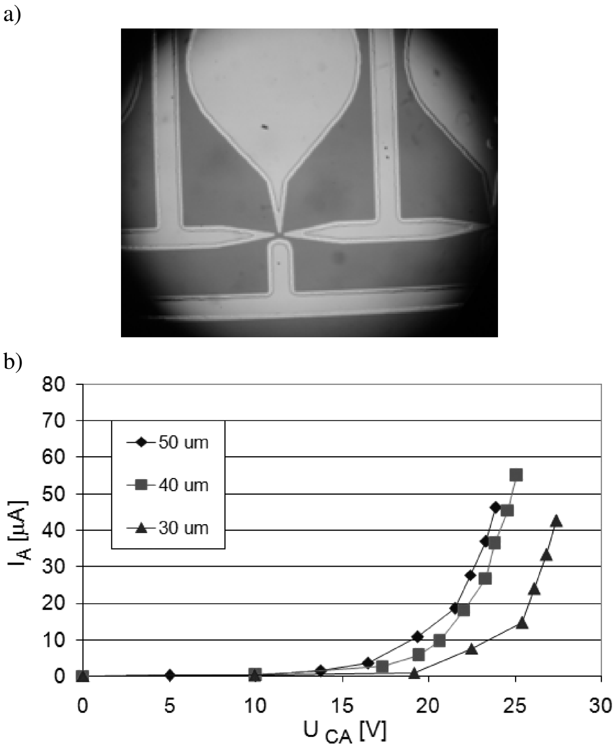

Fig. 7. Lateral field-emission electron source: a) test structure, b) I–U characteristics

4. Conclusions

In the paper a problem of generating vacuum in MEMS-type microsystems was presented. A concept of the orbitron micropump, which can be integrated with silicon-glass or glass MEMS is described. Its construction is to be compatible with the microengineering technology. The most important part of a micropump – a field-emission electron source – was designed and fabricated. The low threshold voltage and a high current density were obtained.

Future works will concentrate on designing all the details of complete orbitron micropump, optimizing electrodes configuration and their proper polarization. Also, technique of getter layer deposition will be elaborated. The theoretical research and first experimental results give a chance for realization of the MEMS-type orbitron micropump.

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