MEMS ion-sorption high vacuum pump

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Abstract. In the article a miniature MEMS-type ion-sorption vacuum pump has been presented. The influence of electric and magnetic field, as well as horizontal and vertical dimensions of the micropump and type of material used for electrodes on the pump properties has been investigated. It has been found that the micropump works efficiently as long as the magnetic field is higher than 0.3 T, and pumping cell is larger than 1×1×1 mm^3. The pump allows generating vacuum at the level of 10^{-7}–10^{-9} hPa in 100 mm^3 volume.

1. Introduction

Different miniature sensors and actuators take advantage of working in vacuum [1]. Moreover, new vacuum micro/nanoelectronics instruments like array X-ray sources, THz sources, and other devices basing on field emission mechanism have been proposed in the literature [2].

Generation, stabilization and measurement of high vacuum inside macro instruments is not a problem up to 10^{-11} hPa or better. In opposite, in microscaled/microengineered MEMS devices the technical limit of long term stabilization of vacuum inside tightly sealed microchamber is still near 10^{-3}–10^{-4} hPa. The most common methods here are vacuum sealing of MEMS followed by gettering of inner gaseous atmosphere. This approach is insufficient because several new possible MEMS instruments should work in at least 10^{-5} hPa kept inside microchamber by at least several hours/days.

Our team has focused onto high vacuum MEMS for at least 5 years. In our previous publications we demonstrated possibility of on-chip pumping of MEMS structures by integrated MEMS ion-sorption micropumps [3, 4]. Here we report a micropump which allows reaching 10^{-7}–10^{-9} hPa in about 100 mm^3 microchamber of a MEMS device.

2. Results and discussion

The micropump reported here is a silicon-glass sandwich structure, consisting of two planar cathodes and one anode with a square via-hole made in its central part (fig 1a, b). Its work is based on the ignition of an electric discharge between the electrodes. The discharge is initiated either by spontaneous or field-emitted electrons cruising inside the micropump cavity, due to the presence of a strong magnetic field generated by two permanent magnets (fig. 1c). Since their paths are very long, they finally hit residual gas molecules and ionize them. The ionized particles are attracted towards the cathodes where they sputter surface layer. In the same time secondary electrons are also generated and a discharge is sustained. Molecules are removed from the microchamber due to chemical reactions with sputtered material and to physical trapping under re-deposited layer.

The construction and working principle of the micropump is similar to the Penning pumps [5], and in part to other partially miniaturized pump presented by Green *et al.*[6]. However, our device is the only one, which is technologically compatible with other MEMS. It is fabricated of silicon and glass by the use of MEMS techniques. It is hermetically sealed by an anodic bonding process and does not require any additional housing. It starts working at about 1 hPa, which can be ensured during encapsulation process performed in the vacuum chamber.

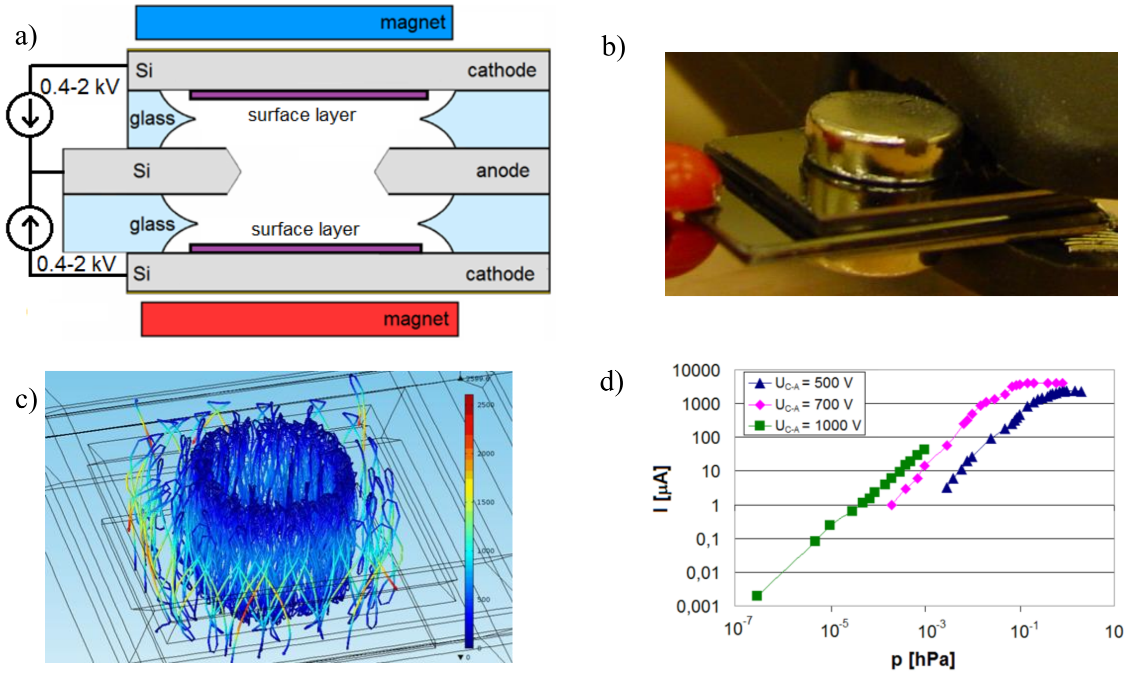

Fig. 1. Ion-sorption vacuum micropump: a) schematic cross-section, b) realization, c) results of simulation of electron trajectory inside a micropump cavity (COMSOL 4.3), d) discharge current vs pressure (calibration curves of the micropump).

The first version of the micropump was 20×12×3.4 mm^3 large (pumping chamber was equal to 6×6×3.2 mm^3). Cathodes of the pump were covered with titanium layer. This devices allowed obtaining 10^{-7} hPa pressure within about 30 min (fig. 1d) [4]. The micropump is still developed, structures with different geometrical and material parameters have been prepared and their properties investigated in different conditions (electric and magnetic field, external pressure level).

Strength of electric and magnetic fields are the most important parameters influencing the micropump operation. Operating voltage varies depending on the pressure, but in any case it should not be lower than 400 V. Without a magnetic field any discharge inside a micropump cavity can be ignited below 10^{-1} hPa (fig. 2a). The larger the magnetic flux density, the smaller the electron orbit and longer the trajectory. Its critical value is equal to about 0.3 T; in this case the diameter of the orbit is smaller than the diameter of the pumping cavity and electron path is almost infinite.

Geometrical parameters (spacers thickness and size of the hole in the anode – equivalents of height and diameter of Penning pump cells) also influence the properties of the micropump (fig. 2b, c). Optimal values are 0.7 mm for the spacer and 2×2 mm^2 for the hole in the anode – they provide the highest discharge current in wide pressure range. The minimal spacer thickness is 0.3 mm and minimal hole in the anode – 1×1 mm^2 – it is still possible to maintain a gas discharge, but the operating voltage needs to be increased to about 1500 V. In smaller microchambers gas ionization is no longer possible.

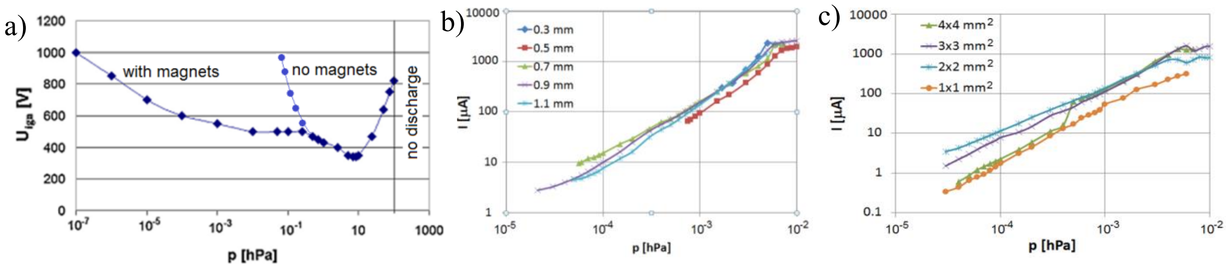

Fig. 2. Results of characterization of the micropump: a) influence of a pressure level on a discharge ignition voltage for structures with and without magnets; b) discharge current vs pressure for different spacer thickness, c) discharge current vs pressure for different size of square hole in the anode.

Apart from the impact of geometrical parameters on micropump performance, also material properties have been examined. Different materials form chemical compounds with different gases and have different sputtering and secondary emission coefficients. Measurements showed, that the *I-p* characteristics obtained for various cathode materials did not differ significantly (fig. 3a), but the highest values of the current were obtained for copper and aluminum layers, while the lowest for tungsten.

Moreover materials exhibiting some "special" properties (ensuring field emission or very high secondary emission) have also been tested (fig. 3b). Cathodes covered with carbon nanotubes (CNT), magnesium oxide and made of porous silicon exhibited superior performance – discharge current increased 10-1000 times in high vacuum range compared to flat silicon [7]. Measurements showed that, it is very likely that the application of MgO allows reaching ultrahigh vacuum inside hermetically sealed MEMS structures (fig. 4), probably even at the level of 10^{-9} hPa (according to the calibration curve). However, this result should be further verified.

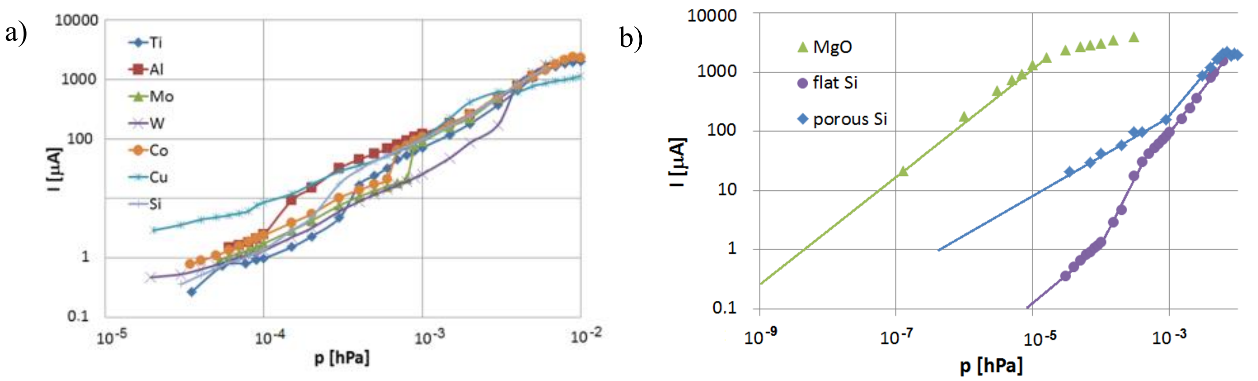

Fig. 3. Characteristics of discharge current vs pressure for: a) silicon cathodes covered with various thin film metals, b) comparison of a flat and porous silicon cathodes and a cathode with MgO layer.

The obtained result – generation of high vacuum (10^{-7}– 10^{-9} hPa) by a MEMS micropump – opens a way towards invention of a new class of high-vacuum microdevices and integrated MEMS instruments [8]. Our recent works are focused onto elaboration of Rb/Cs optical MEMS cells equipped with on-chip micropumps in which at least 10^{-7} hPa will be stably maintained. An example of high-vacuum optical cell is shown in the fig. 4.

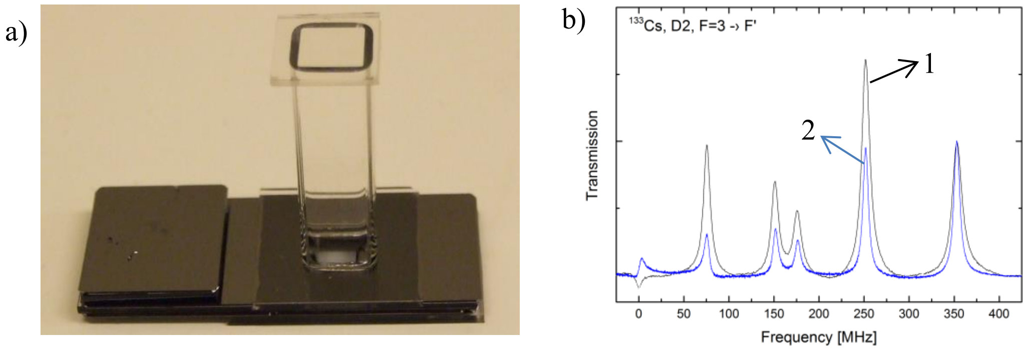

Fig. 4. Cesium optical MEMS cell integrated with a micropump: a) image of the structure, b) Doppler-free absorption spectroscopy (black line 1 – MEMS cell, blue line 2 – reference cell). The cell sealed anodically, pumped by an on-chip micropump and Cs laser-dispensed, final vacuum ~10^{-6} hPa.

3. Conclusion

In the article we have demonstrated the first miniature ion-sorption pump which is able to generate high/ultrahigh vacuum in MEMS devices. The influence of magnetic and electric field, as well as geometrical and material parameters of the micropump on the ionization process have been carefully investigated. Micropump works well until magnetic field is larger than 0.3 T, voltage is properly adjusted to the pressure level and pump microchamber is at least 1×1×1 mm^3. Application of magnesium oxide on the cathode allowed significant improvement of micropump performance and obtaining 10^{-9} hPa. The micropump can be self calibrated and can work also as a vacuum gauge.

Realization of the micropump which enables ensuring stable high vacuum in microvolume opens a way for fabrication of a new class of microsystems which works in vacuum range well below 10^{-5} hPa.

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