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MEMS-Compatible X-Ray Source

P. Urbański and T. Grzebyk

***Abstract*— In this letter we present the first stand–alone X-ray source made in MEMS (micro-electro-mechanical system) technology, which is able to operate outside a vacuum chamber. We have overcome the existing problems with hermetic sealing, high vacuum stabilization and risk of electric short-circuits which have so far prevented the realization of such a device. The source is 30 × 16×7 mm^3, operates up to 30 keV, with currents reaching few hundred microamperes. Due to the technological compatibility with other MEMS structures and possibility of adjusting its parameters, this source can be easily applied in different X-ray experiments performed in micro scale. [2024-0103]**

***Index Terms*— Integration, micro electro mechanical systems (MEMS), miniaturization, X-ray source, field electron source.**

I. Introduction

X-RAY radiation, due to its unique properties, finds application in a wide variety of fields, from medical diagnostics and therapy to industrial and research endeavors. In today's dynamic world of technological innovation, miniaturization and integration are key drivers of progress. These trends are visible also within the realm of X-ray technology. Number of research groups work on utilization of X-ray radiation in miniature systems (MEMS and μTAS – micro Total Analysis Systems). People investigate the influence of radiation on cells and microorganisms, use it for analyzing heavy-metal pollutants in water flowing through a microchannnels or characterizing chemical reactions that take place in liquid samples [1], [2], [3], [4]. What is interesting, in all these cases radiation is still generated by conventional, large-scale X-ray sources or even synchrotrons.

On the other hand, the existing literature documents various miniature X-ray sources employing different mechanisms for electron emission and electron-radiation conversion.

For instance, sources that utilize the pyroelectric effect, thermal or field emission have been developed throughout the years [5], [6], [7], [8], [9]. These sources have shown promise in terms of size reduction and efficiency improvements.

Very often some elements of those novel sources are manufactured by microengineering or even nanotechnology.

It applies especially to the field emission cathodes, which are responsible for the emission of electrons [10], [11], [12], [13]. However, up till now there has been no complete device made only in MEMS technology. Elements like electron optics column, target, X-ray window, housing are most frequently manufactured and integrated by classical methods used in vacuum technology for more than 50 years [14]. Few examples of more integrated structures have never operated outside the vacuum chamber, as stand-alone devices [15], [16].

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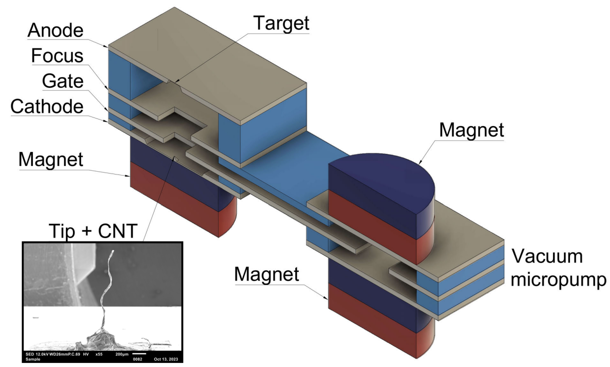

Fig. 1. Construction diagram of a MEMS X-ray source.

Thus, there is a technological miss-match between miniature, MEMS-based platforms in which experiments utilizing X-rays are performed and more-or-less miniature X-ray sources which are (or can be) applied in them. Authors see the chance for combining these two worlds, but this requires the development of completely MEMS-based sources.

In this letter we present for the first time an X-ray source where MEMS technology was applied not only to the electron source, but also to all other elements, enabling potential integration with rest of the experimental system. Moreover, due to flexibility in polarization conditions and target design, the source enables generation of a beam with a desired characteristics (energy and spectrum).

II. Design

The developed MEMS X-ray source is made solely out of silicon and glass wafers. Silicon chips form the electrodes: a cathode with a field emitter, an extraction gate, a focusing electrode and a target. Borosilicate glass is used for preparation of spacers between the electrodes [Fig. 1].

The electron source used in this device is made out of a composite of carbon nanotubes and PVP (polyvinylpyrrolidone) in the form of a needle deposited onto a silicon substrate by thermo-mechanical method [17].

The extraction electrode is made of silicon with an etched via-hole with dimensions of 2×2 mm^2. It allows the control of the emission current and, as a result, the intensity of the generated X-ray radiation. The focusing electrode is made of silicon with an etched hole measuring 3×3 mm^2. It enables electrostatic focusing of the electron beam. The target is a silicon chip with a thin 2 mm×2 mm×15 μm membrane.

The X-ray source is integrated with an ion-sorption pump, responsible for providing high vacuum conditions. The design of this micropump includes two flat silicon cathodes, two glass spacers,

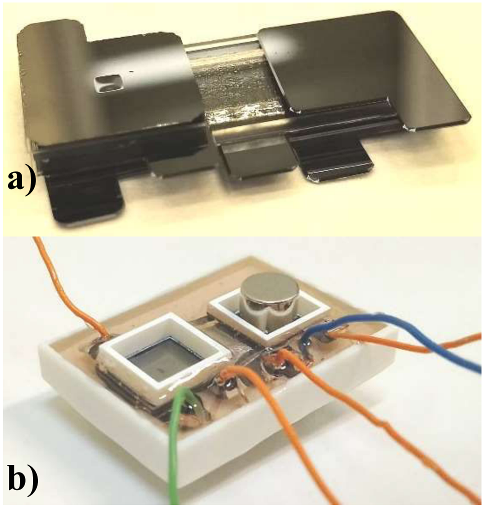

Fig. 2. a) Image of the MEMS X-ray source structure, b) complete, encapsulated MEMS X-ray source with a protective polymer layer.

a silicon anode placed in the middle and two neodymium magnets placed on both sides of the micropump [18]. The connection between the X-ray source and the pump is made through a channel etched in the glass they share, sealed with a common silicon electrode.

The external dimensions of the complete structure are 30×12 mm^2. The height of the X-ray source column is 6.2 mm. The distances between the electrodes have been optimized. There is only 0.5 mm from the cathode to the gate, to ensure high emission currents for a relatively low voltage. Between the gate and the focus electrode there is 1.1 mm. The distance to the target is the largest – equal to 3 mm. It was necessary for supplying this electrode with very high voltages (up to 30 kV), without a risk of short-circuits and without affecting the potential distribution near the cathode. In this way one can have independent control over all parameters of the beam: the current, energy and focal spot.

The developed X-ray source operates in a transmission mode. Electrons emitted from the electron source are accelerated by a strong electric field. The generated beam of high-energy electrons hits the target, which causes the emission of X-rays as a result of braking the particles on the anode material (so called Bremsstrahlung radiation) and ejection of electrons from the internal electron shells (characteristic radiation) [19]. The spectral characteristics of the generated radiation depends on the power supply parameters as well as the material and thickness of the target – all can be adapted to different applications. The silicon target can be covered with a nanometric layer of metallization, e.g. tantalum or nickel, in order to improve the monochromaticity and intensity of the resulting X-ray radiation, which has also been tested [20].

All silicon and glass elements were connected using the anodic bonding method, with the last bonding performed under vacuum conditions (10^{-5} mbar) to ensure initial vacuum inside the structure. The actual structure of the MEMS X-ray source is shown in Figure 2a. In order to protect the structure against external breakdowns between the electrodes, after preparing the electrical contacts, the whole chip was covered with an epoxy resin, creating a complete stand-alone MEMS device [Fig. 2b].

III. Measurements and Tests

The X-ray source was hermetically sealed, thus all measurements could be performed for the first time outside a vacuum chamber, in air. First, the ion-sorption pump was turned on. It ensured a stable high vacuum within the structure at the level of 10^{-7} mbar, and kept it constant during device operation.

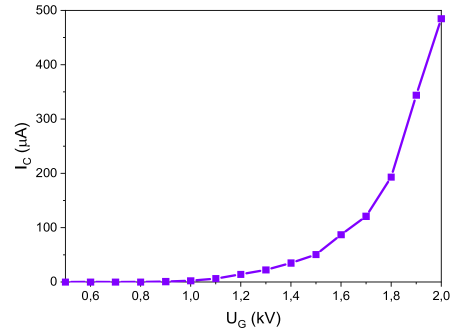

Fig. 3. Emission current vs extraction electrode voltage.

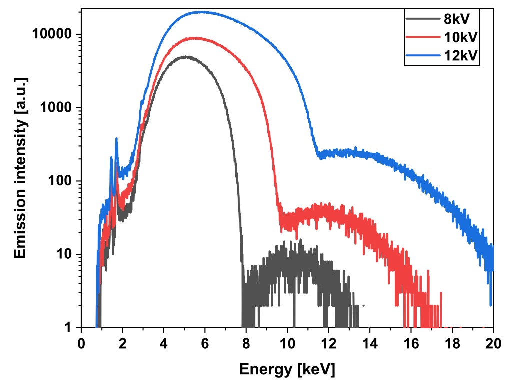

Fig. 4. X-ray spectra emitted by a MEMS X-ray source for different anode voltage U_A.

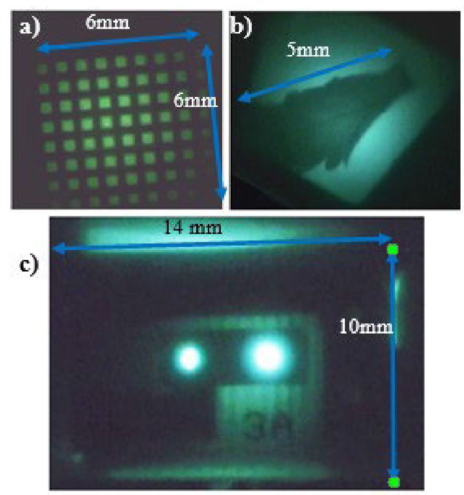

Fig. 5. X-ray image of: a) a silicon mesh (UA = 10kV), b) a leaf (UA = 12kV, c) PCB: light spots - via-holes, black area - metal, green area - laminate (UA = 30kV).

The CNT electron source provided high emission current, even for low voltages at the extraction electrode (up to 500 μA for 2 kV) [Fig. 3], which ultimately allows to obtain an efficient and intense X-ray beam.

Measurements of the radiation spectra generated using the constructed X-ray source were performed for 3 different voltages accelerating the electron beam. Measurements were made for a distance of 10 cm between the X-ray source and the head of the spectrometer. The measured spectra showed high Bremsstrahlung signal for energies between 4 and 8 keV and only a low intensity of characteristic silicon peaks of 1.46 keV and 1.71 keV [Fig. 4]. This is due to the strong attenuation of low-energy X-ray radiation (<5keV) by air. In previous studies, in which measurements were performed inside a vacuum chamber, the characteristic peaks contained most of emitted energy [20]. The design of the source allows for free manipulation of the energy of the emitted radiation by changing the voltage that accelerates the electron beam applied to the target or by changing the target material.

The developed MEMS X-ray source was used for now as a stand-alone device for taking X-rays images of small objects [Fig. 5]. When thin and soft objects are inspected, energies in the range between 10 and 15 keV are sufficient for obtaining high-contrast pictures. For thicker objects, like PCB, energy must be increased to 25-30 keV.

However, its technological compatibility offers the potential for future integration with MEMS-based platforms and for conducting whole X-ray experiments within a single chip.

IV. Summary

The letter presented a breakthrough achievement in the field of MEMS and vacuum technology - the creation of the first X-ray source fully based on MEMS technology.

The X-ray source has been designed in a way that allows precise control of electron emission and focusing of the beam, which translates into effective generation of X-ray radiation (energy up to 30 keV, current – hundreds of microamperes). Integration with an ion-sorption pump ensures a stable level of high vacuum inside the structure (down to 10^{-7} mbar).

The experimental results confirmed that the MEMS source can be an alternative to other miniature sources. It has a similar size, maybe it does not offer as high energy and power as competitive solutions (they operate up to 65 keV, with currents above 1 mA), but the used technology allows for new applications. After integration with other MEMS platforms one can conduct biological, medical and analytical experiments in micro scale.

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