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Chip based MEMS Ion Thruster to significantly enhance Cold Gas Thruster Lifetime for LISA

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Abstract. Micropropulsion is a key component for ultraprecise attitude and orbit control required by the eLISA mission. LISA pathfinder uses cold gas micro thrusters that are accurate but require large tanks due to their very low specific impulse, which in turn limits the possible mission duration of the follow up eLISA mission. Recently, we developed a compact MEMS ion thruster on the chip with a size of only 1cm² that can be simply attached to a gas feeding line like the one used for cold gas thrusters. It provides a specific impulse greater than 1000 s and only requires a single DC voltage. Since the operating principle is based on field emission, very low thrust noises similar to FEEP thrusters are expected but with gas propellants. The MEMS ion thruster chip could be mounted in parallel to the existing cold gas system providing high Isp and therefore long mission durations while leaving the cold gas system in place. To enable a possible mission extension, the MEMS ion thruster could take over from the cold gas system as a backup while maintaining the existing micropropulsion thruster system with its heritage therefore minimum risk.

1. Introduction

Micropropulsion systems are of high interest for the LISA mission due to precise thrust control in a wide range as well as exact and reliable attitude and orbit control. LISA pathfinder uses 6 cold gas thrusters with an accurate thrust in a range of 10 to 500 μ N which contains a mass flow sensor with a piezo-controlled valve [1]. Concerning the very low specific impulse of only 50s already 40% of the high-pressure Nitrogen propellant have been used during the first few months of LPF mission [1]. The low efficiency of the described propulsion system and the very large tanks will in turn limit the lifetime of the follow-up eLISA mission. NASA provided the DRS package which features a Colloid thruster with a larger specific impulse of up to 1500s, however the maximum thrust range is only 35 μ N which is not sufficient for the full eLISA mission [2]. Various micropropulsion systems have been studied as possible candidates for eLISA.

Here, we are going to present a new and simple design called MEMS ion thruster [3] that can use the cold gas infrastructure and provide ion thruster performance. It uses the well-established principle of field emission combined with gas propellant thus eliminating all propellant-related wetting and contamination issues that are common for FEEP or Colloid thruster. Based on the recent development of our thruster chip with a size of less than 1cm², our system could significantly increase the lifetime of eLISA and create the possibility for mission extensions. As an add-on to the existing cold gas thruster units, the heritage and reliability of the system are retained while the possible specific impulse is



increased to the 2000s-range. The principle of function responds to electrostatic field emission using the same gas propellant like the cold gas system and providing an ionization efficiency up to 30%. A low thrust noise similar to the ones of FEEP of Colloid thrusters is expected. By switching the polarity of the required single DC power supply, the emitter chips can be simultaneously used as a neutralizer. The MEMS ion thrusters can employ the existing gas feeding system as well as the gas propellant and uses the cold gas thrusters as a backup. Therefore eLISA benefits from high specific impulse, high propulsion efficiency and a significantly enhanced lifetime with minimal risk.

2. MEMS Gas Field Ionization Source Thruster

This chapter will outline the principle of function of the MEMS field ionization thruster and introduce previous works. A review of the novel manufacturing method, as well as first results of MEMS ion thruster prototypes, are given.

2.1. Review of the Concept

The MEMS field ionization thruster is taking advantage of the basic gas field ion source (GFIS) which already has been invented in 1951. The gas is ionized in an electric field between an anode (tip) and a cathode (grid) and the ions are accelerated in the field (Figure 1). The substitution of the vintage anode tip geometry by an aligned CNT forest could lead to high ionization volume and consequently higher ionization efficiencies. The opportunity to emit both gas ions and electrons depending on the polarity of the DC power supply is another positive aspect of GFIS which eliminates the need for a separate neutralizer.

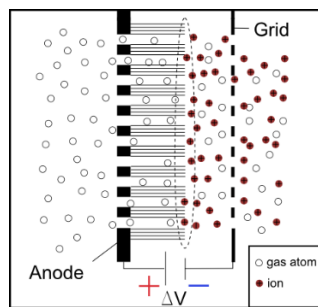


Figure 1. MEMS Gas Field Ionization Source (GFIS) Thruster with illustrated high ionization area in gas ion emission mode.

Previous attempts in the development of MEMS GFIS have been done at MIT and NASA Ames Research Center [4,5]. Both evolutions proved the functionality of MEMS GFIS but they struggled in various details of the manufacturing approach. As shown in Figure 2 the flow-through silicon μ Foam with CNTs of MIT have serious restrictions due to poor CNT homogeneity which corresponds to poor ionization efficiency. In consequence of the strong field enhancement between the single CNTs, the MIT obtained ionization potentials of 300V only. NASA abandoned the development of a flow through GFIS and concentrated on flow-past patterned electrodes (Figure 3) as a result of unexpected challenges in the etching procedure of the silicon chip. The developed electrodes achieved continuous CNT growth leading to ion currents up to 100 μ A and electron currents up to 400 μ A.

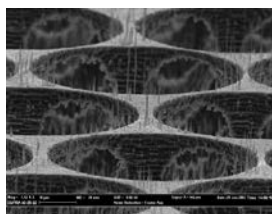


Figure 2. Flow Through Electrode by MIT [4]

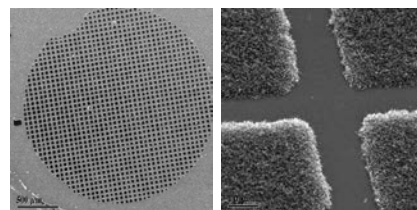


Figure 3. Flow Past Electrode designed by NASA Ames [5]

2.2. Chip Design and Manufacturing Process

The field ionization source is an assembly of silicon chips which are easily scalable to fit in the needed application. We manufactured both round and square chips with slits or holes working as gas feed through. For the mechanical treatment, we partnered up with the Laserzentrum Mittweida for laser manufacturing of the chips. The laser drilling process enables a fast alteration of the shape parameters to investigate various arrangements and represents a less risky process to generate small hole diameters to attain high aspect ratios for high ionization efficiencies. In cooperation with the Fraunhofer Institut für Keramische Technologien und Systeme (IKTS), the CNT deposition is implemented with the atmospheric pressure chemical vapor deposition (APCVD) process. The manufacturing procedure is shown in Figure 4.

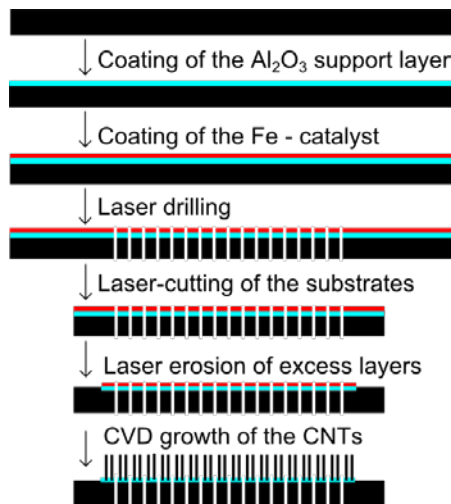


Figure 4. Manufacturing approach for flow through electrode

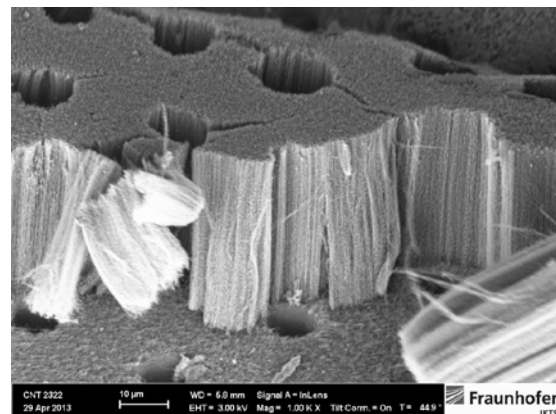


Figure 5. Results of Laser Drilling and CNT-Deposition

Highly n-doped low resistance 100mm silicon wafers are used as base material. In a first and second stage, the wafers are coated with an Al_2O_3 and a Fe-catalyst layer. Both are crucial for the following CNT deposition since the CNT growth site is defined by the nm-sized Fe-particles. To prevent a possible damage of the CNTs the laser manufacturing is performed as the third stage. Therefore, a pulsed UV laser CNC drilling machine is used processing the silicon chips from the back to minimize the pollution of the coated surface. In a finale stage, the APCVD-process is accomplished at IKTS. With a process duration of 80min and temperatures of 700°C CNTs with a maximum length of $130\mu\text{m}$, high density, a very close growth near the holes and a high uniformity are achieved as shown in Figure 5.



Figure 6. Test module design and laboratory model

2.3. Test module design and test results

The design of the developed test module for field emission and field ionization is shown in Figure 6. A modular setup with a PEEK case and copper contact electrodes has chosen for performance tests of various configurations.

Initial tests were performed with a chip design with 20mm outer diameter and Argon was chosen for the gas field ionization test due to its availability at the lab. First experiments are realized in the electron-emission mode at a pressure of 10^{-6} mbar. The initial voltage for electron emission is in the area of 220V only, with electron currents up to 1mA are easily reachable. As shown by the results in Figure 7, no higher electron currents are attempted to prevent the thruster from early damage.

Further experiments were performed in the ion-emission mode by switching the polarity of the DC power supply and enabling the gas feed through. I-V characteristics for mass flow rates between 0.6sccm and 2.2sccm are plotted in Figure 8. As higher mass flow rates will increase the possibility of arc discharges inside of the plasma generator the tests were operated at low voltages to prove and demonstrate its functionality and true bipolar capability.

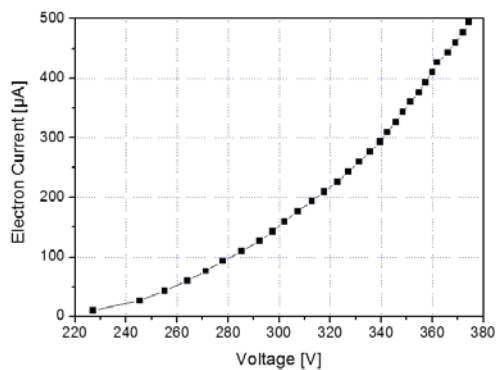


Figure 7. Results of I-V characteristics in electron emission mode.

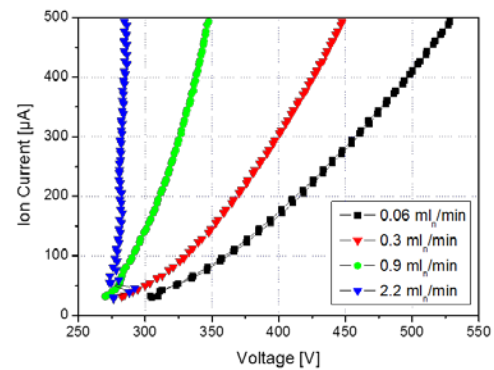


Figure 8. Results of ion emission with various gas flow rates.

Subsequently, the highest achievable ionization efficiency was determined by a gas flow rate of 0.06sccm Argon. The higher the applied voltage the more gas will be ionized inside of plasma generator for a good efficiency. The limit was set just below micro discharges occur. As plotted in Figure 9 the maximum was found at 740V with an ion current of about 1.2mA. The measurement data enables the calculation of the ionization efficiency to 28% with a specific impulse of 1700s and a total thrust of close to 30µN (Figure 10).

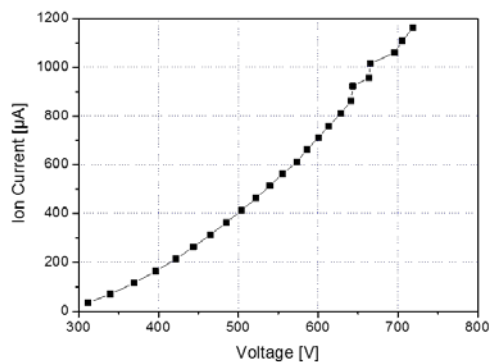


Figure 9. I-V characteristics with Argon at 0.06sccm for maximum achievable current

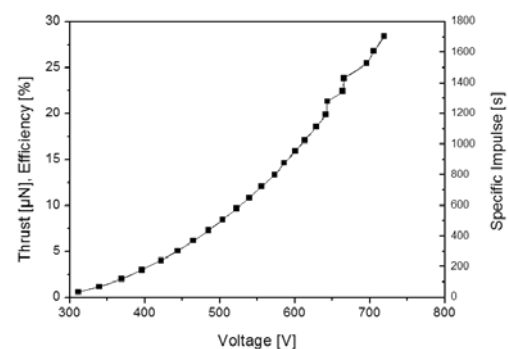


Figure 10. Thruster-related performance for a flow rate of 0.06sccm Argon propellant.

The MEMS gas field ionization thruster can be used with any kind of gas propellant. eLISA will use Nitrogen which is lighter and has a lower ionization potential than Argon. Accordingly, an even higher specific impulse is expected. With the flow rates of LPF, thrusts even in the mN-range are possible.

3. Integration of MEMS Ion Thruster to eLISA

The integration of MEMS ion thruster involves minimum risk to the eLISA mission while enabling the lifetime enhancement of the cold gas thruster system and the possibility for mission extensions. At an electric potential of 500V the estimated specific impulse for Nitrogen is 2150s, which increases the lifetime of the propellant by a factor of 48. By keeping the cold gas thrusters, the heritage and reliability of the overall thruster system for eLISA will be retained. Two considerable integration methods are illustrated in Figure 11.

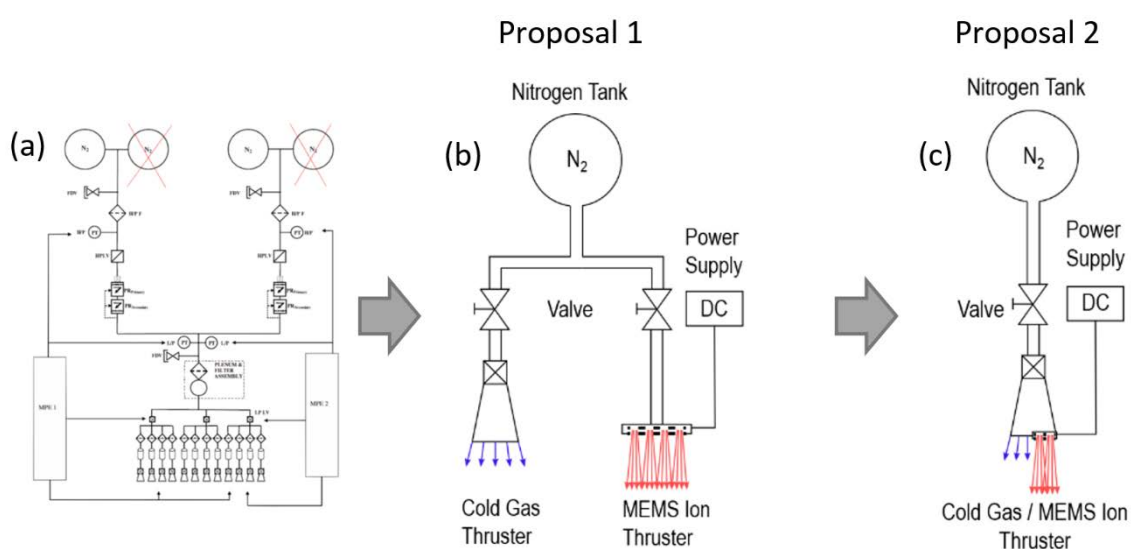


Figure 11. Considerable integration methods of MEMS ion thruster by keeping the heritage of the cold gas system. The existing cold gas system (a) could benefit from high specific impulse of electric propulsion with parallel integration (b) or hybrid integration (c).

Both configurations abandon separate neutralizers as well as magnetic fields for gas ionization. For the generation of plasma only one DC power supply is needed. The MEMS ion thruster could be mounted in parallel to the existing cold gas thruster system using the same gas feeding line and gas flow sensor. This option requires an additional piezo valve for enabling the gas flow to the MEMS ion thruster. The second option presents an integration of the MEMS chip into the existing cold gas thruster nozzle. Without applied voltage to the MEMS ion thruster, the cold gas thruster can operate as usual. By activating an electric potential, it will benefit from high efficiency and improved specific impulse.

4. Summary

A novel silicon chip based MEMS ion thruster has developed and tested. An ion beam is generated at the tip of a forest of carbon nanotubes with combines the simplicity of field emission electric propulsion with ion thruster technology thus only a single DC power supply is required. Moreover, by switching the polarity, the thruster can operate in an electron emission mode as well which eliminates the necessity of a separate neutralizer. Magnetic fields or heater units are not needed for the thruster operation. Expecting very low thrust noise an integration to eLISA mission should be considered to benefit from high specific impulse as well as high propellant efficiency. The MEMS ion thruster could increase the

propellant lifetime of eLISA by a factor of 48, improve the maximum thrust capability and enable possible mission extensions.

Two proposals were presented for a possible integration to eLISA mission. Both retain the heritage and reliability of the existing cold gas system by keeping it in place. The MEMS ion thruster could be operated in parallel or in a hybrid mode. The case of complicity is considered by switching back to the heritage cold gas system thus a minimum risk to eLISA mission.

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