Micromachined Mass Spectrometer for Low-cost Space Missions

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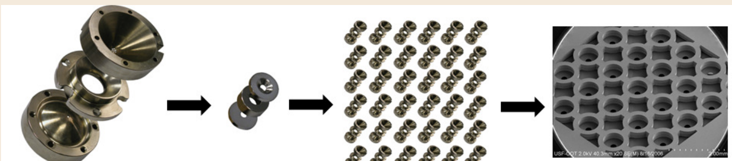
Preface

Scientific space missions, such as investigating the substances in comets, provide essential information regarding the nature of the universe. Comets carry interstellar and nebular materials that are pivotal to understanding the pre-biotic molecules that could have initiated life on earth. Although launching space missions to collect and analyze these materials is very costly, the radical miniaturization of scientific instruments for space applications greatly reduces a multi-science mission payload. Mass spectrometers (MS) are powerful tools for chemical analysis and, when miniaturized, are optimal for space applications. The goal of this work is to surpass the current miniaturization of space-flight MSs by using microelectromechanical system (MEMS) technology for the exploration of chemical distributions in space.

Approach

Cylindrical 3-D ion traps (CITs) offer a good approximation and simplification of the hyperbolic-shaped Paul's traps. Miniaturization of CITs allows operation at much lower voltage and power for the same mass range, while reducing size, weight, and driving electronics complexity. Although the reduction in size (r_0) leads to reduced ion trapping capacity, this is countered by incorporating an array of miniature traps that, combined, still operate at a lower voltage. The relatively shallow potential well of these miniature CITs, as compared to the larger counterparts, requires higher machining precision, smoother surfaces, and dimensional uniformity across the array for optimum performance. To meet these exacting requirements, a MEMS fabrication and assembly approach has been adopted to micro-machine high precision μ-CIT arrays in silicon (Si) wafers. A custom-designed electron source and a detector system are also being developed to support the simultaneous operation of all the traps across the array.



r_0= 0.036 cm

QIT r_0= 1 cm
- Hyperbolic ion trap used in most commercial instruments
- Difficult to machine
- High voltages required

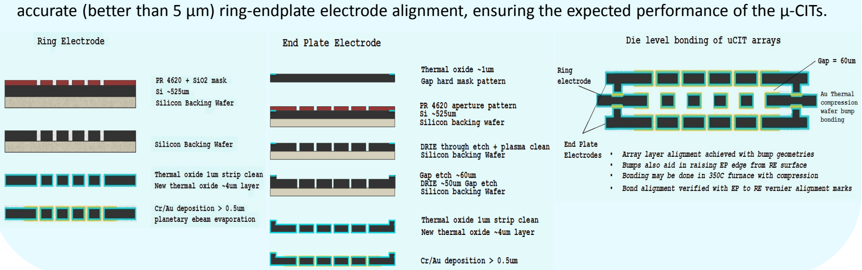
CIT r_0= 0.2 cm
- Cylindrical ion trap (CIT)
- Similar trapping potential
- Easier to further miniaturize

Array Approach
- Regain sensitivity by increased trapping volume
- Parallel analysis through multiple sub-arrays

Microfabrication Approach
- High machining precision
- Batch fabrication leads to cost effective and repeatable process
- High uniformity across the micro (μ)-CIT array

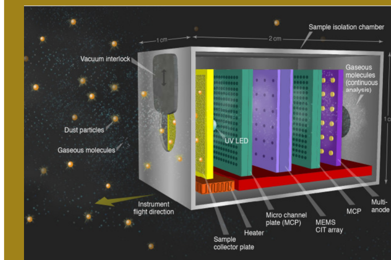
MEMS Fabrication

The electrodes to build a complete μ-CIT array with trap r_0 ~ 360 μm are micromachined in Si wafers. Three-substrate precision alignment and bonding processes results in a complete μ-CIT array. Lessons learned from previous design versions of μ-CIT arrays are incorporated into the latest μ-CIT MEMS design to significantly reduce device capacitance (C_p <30 pF), improve alignment accuracy, minimize process failure modes, and reduce bonding complexity while increasing the voltage range that can be applied to the electrodes without an electrical breakdown. A series of iterative Si oxidation-isotropic etch processes is used to maintain smooth surfaces and edges on the electrodes to avoid undesirable field emissions. A passive-alignment feature allows mechanical locking of the electrodes during the bonding assembly of the μ-CIT chips to enable repeatable and accurate (better than 5 μm) ring-endplate electrode alignment, ensuring the expected performance of the μ-CITs.

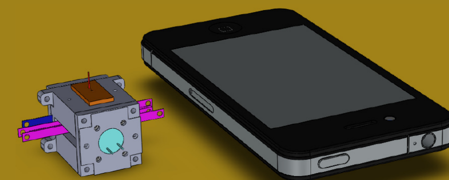


Device Concept and Packaging

The smallest commercially available microchannel plates (MCPs) dictated the overall form factor of the μ-MS assembly. The shape of the μ-CIT array chip and other custom ion optics was adjusted accordingly. As a phase 1 low-cost design approach, a package (<10 cm³) was designed in ULTEM 2100 (10% glass reinforced) for a compact assembly of all the μ-MS components. The μ-MS package, housed in a miniature vacuum chamber (3x3x5 cm³), will be used to characterize the MS performance for up to 250 atomic mass units. A provision to cool down the μ-MS package is provided for fast absorption and desorption of molecules from the sample collector plate. All ion optics components inside the μ-MS package are stacked together and aligned by the inside corners of the ULTEM package and lightly compressed with four set screws.

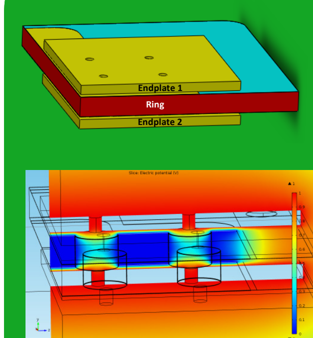


A rendering of a concept mission deploying the prototype μ-MS for analyzing particles and molecules from cometary jets.

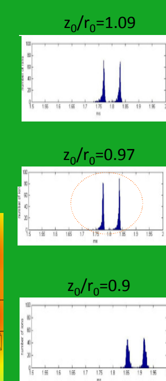


μ-MS package next to an iPhone-4 for size comparison.

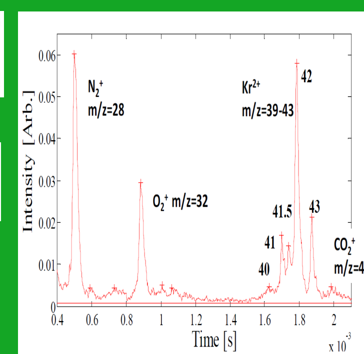
Performance



A 1/4th model of the real size μ-CIT array to simulate expected capacitance of the prototype device in COMSOL. Calculated C_p in the range of 20-30 pF.



A series of simulations with various geometries. z_0 ranges from 270 to 325 μm, and r_0 varies from 250 to 350 μm. Optimized mass resolution is as z_0/r_0 approaches 0.97.



Results measured from a previous version of μ-MS. A spectrum of Krypton²⁺ and background earth atmosphere.

References

Ashish Chaudhary, Friso H. W. van Amerom, and R. Timothy Short , "Development of Microfabricated Cylindrical Ion Trap Mass Spectrometer Arrays", *Journal of Microelectromechanical Systems*, Vol. 18, No. 2, April 2009

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