Mass Analysis, Directed Ion Transfer, and Field Shaping in Lithographically-Patterned Planar Ion Traps

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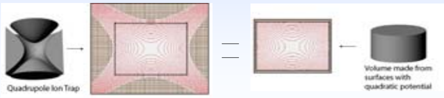
Abstract

We have developed a series of radiofrequency ion traps using pairs of lithographically-patterned ceramic plates. Both 3-D and 2-D quadrupoles have been demonstrated, as well as an interesting arrangement in which both a 3-D quadrupole and a toroidal trapping field are created simultaneously and coaxially. In this coaxial ion trap, ions can be trapped in the toroidal region (which has a significantly larger storage capacity), transferred to and trapped in the 3-D quadrupole, and then mass analyzed. Although all of these devices rely on trapping fields that are primarily quadrupolar, the electrode patterns allow independent adjustment of higher-order components, e.g., hexapole, octopole, decapole, etc. We can also perform dipole resonant excitation resulting in either ion ejection or collision-induced dissociation. As mass analyzers these devices have demonstrated resolving power in excess of 1000 (m/Δm). These devices have a very open structure, allowing easy access for lasers, incident particle beams, and optics.

Conceptual/Theoretical Basis

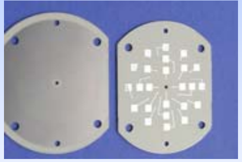
The electric potential distribution within any volume of space is found by solving the Laplace equation, using known potential surfaces (i.e., electrodes) as boundary conditions. Boundary conditions do not have to be equipotential surfaces, such as metal electrodes. Non-equipotential surfaces also produce potential distributions. For instance, the familiar three hyperbolic electrodes shown below produce a quadrupolar potential distribution. Similarly, a cylindrical solid on which each surface has a quadratically varying potential function will also produce a quadrupolar potential distribution. Indeed any real potential distribution can be made by applying the corresponding potential functions to any closed surface. We are using planar electrode arrays covered with a resistive layer, in which potential functions are superimposed to produce any desired trapping potential. As with conventional ion traps, however, edge effects are still an issue. Ion traps made using this approach have several potential advantages. For instance, electric trapping fields can be optimized by changing the potential function on the plates rather than by changing the physical electrode spacing or dimensions.



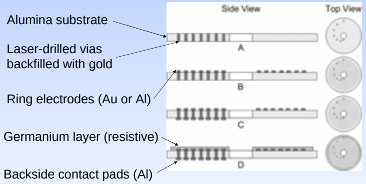
Trap Plate Design

Trap plates begin as alumina substrates, 0.65 mm thick and 46 mm diameter. Holes are laser-drilled for vias (electrical connections between front and back sides) which are then filled with gold. Holes for ion ejection and for mounting are also laser drilled. Aluminum electrode rings are photolithographically deposited in the trapping side, and connections and contact pads are patterned on the backside. A thin layer of germanium is deposited on top of the rings on the trapping side. Potentials are applied to the trap using an RF power supply. The potential on each ring is set using a capacitive voltage divider. Supplementary voltages (ac or dc) can be applied to specific rings, or to just one plate. The germanium layer prevents charge build-up and evens out the potential applied by the rings.

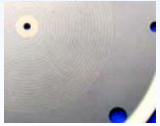
Trapping plates, front and back sides



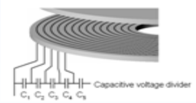
Fabrication and lithography steps to produce plates



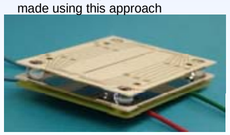
Enlargement in which aluminum rings can be seen through the germanium



Arrangement of electrode rings, vias, and capacitive voltage divider



A linear ion trap has also been made using this approach

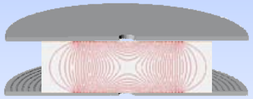


Two-plate Quadrupole Ion Trap

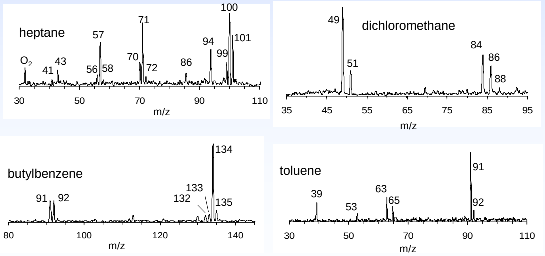
We have developed and demonstrated a quadrupole ion trap (Paul trap) made using two plates. A 1-mm hole is used for ion ejection. The spacing between the plates is adjustable, but most experiments were done using a plate spacing of 5 mm, corresponding to a z_0 value of 2.5 mm. Shown at bottom are spectra of several organics taken using a dipole resonance ejection scan, with drive RF at 1.1 MHz, ramped from 250-750 $V_{0\text{-}p}$, operated using 1 mtorr of helium as buffer gas. Higher order multipoles can be modified by changing the potentials on each ring—a simple electrical change rather than changing the physical shape of spacing of metal electrodes.

Photograph of the two-plate quadrupole ion trap

Equipotential lines in the two-plate quadrupole ion trap



Typical mass spectra from the two-plate Paul trap (planar Paul trap).



Varying Higher-Order Multipoles

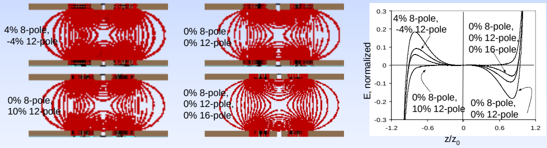
Cylindrically symmetric potential distributions can be expressed as:

$$\Phi(\rho,\theta,\phi,t)=\Phi_0(t)\sum_{l=0}^{\infty}A_l\left(\frac{\rho}{r_N}\right)^l P_l(\cos\theta)$$

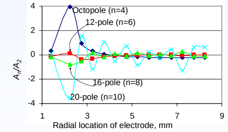
$$\Phi_{r,z}=\Phi_0\left(A_0+A_1\frac{z}{r_0}+A_2\frac{r^2-2z_0^2}{2r_0^2}+A_3\frac{3r^2z-2z^3}{2r_0^3}+A_4\frac{3r^4-24r^2z^2+8z^4}{8r_0^4}+\ldots\right)$$

quadrupole (*l*=2), hexapole (*l*=3), octopole (*l*=4), etc. In primarily quadrupolar devices the terms with *l*>2 are referred to as higher-order multipoles. These terms can be independently controlled and adjusted using our multiple-electrode design simply by changing the RF amplitude applied to each ring.

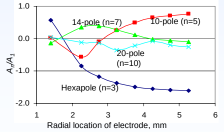
Isopotential plots of "quadrupole" ion trap configurations with varying 8-, 12-, and 16-poles. Magnitude of higher-order poles is expressed as a percent of the quadrupole.



The same potential applied to rings on both plates (even-order terms)

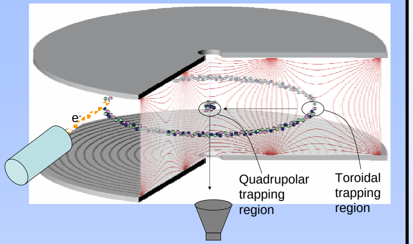


Opposite potential applied to a given ring on each plate (odd-order terms)

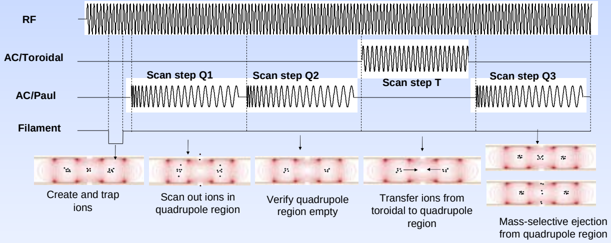


Coaxial Ion Trap

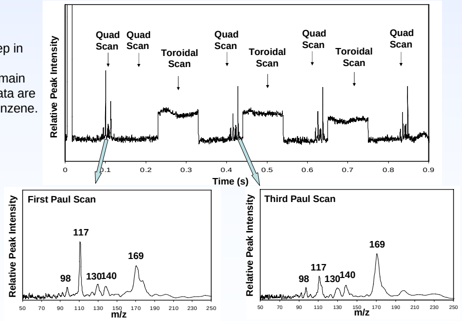
The coaxial ion trap is a two-plate device in which both quadrupolar and toroidal trapping regions are created simultaneously and coaxially. Ions can be trapped in either region, can be transferred from the toroidal region to the quadrupolar region, and mass-selectively ejected from the quadrupolar region. The Coaxial trap is made using the exact same set of plates as the quadrupole trap described to the left, the only difference being the RF amplitudes applied to each electrode ring.



For experimental characterization, electro ionization created ions in situ. Ions were then mass-selectively ejected out of the quadrupole trap. A second quadrupole scan verified that the quadrupole trap was empty. Ions were then transferred from the toroidal trapping region to the quadrupole region using an applied ac signal. The Quadrupole region was then scanned again and the transferred ions were mass-selectively ejected. Below is the scan sequence. Many other scan sequences have been demonstrated, including multiple transfer steps and mass analyses.



Representative data from coaxial ion trap. Each step in which the quadrupole is scanned yields a time-domain mass spectrum. These data are from bromopentafluorobenzene.



Acknowledgement

This work is generously funded through grants from the NASA Planetary Instrument Definition and Development Program, and the Department of Defense SBIR program.

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