The Planar Electrode Linear Ion Trap

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Abstract We present a linear type ion trap consisting of metal lines that are lithographically patterned onto two ceramic substrates. Trapping fields are realized by applying specific voltage potentials to each line. This arrangement allows miniaturization approaches that are immune to surface roughness issues and increased complexities of precision machining of electrode surfaces. We also present how these traps allow a thorough study of higher order multipoles and their effect on mass analyzer performance.

1. Introduction

Ion traps have been used in many mass spectrometry applications. These applications include use in the fields of biology, analytical chemistry, forensics, and space exploration. Additionally, there has been progress towards using ion traps to implement quantum computing[1]. Ion traps have been useful in a broad range of applications due to their inherent sensitivity and specificity. The relative simplicity in miniaturization and higher operating pressures also increase the attractiveness of ion trap mass analyzers[2].

There are many approaches being taken to miniaturize ion trap systems. The quadrupole ion trap lends itself the easiest to miniaturization due to ion stability at relatively high operating pressures[3]. One of the great difficulties in miniaturizing conventional quadrupole ion traps is in the available precision in machining and aligning hyperbolic metal electrodes or circular rods[4]. Some of the approaches to miniaturization have involved the simplification of electrode geometries for easier machining. These approaches include cylindrical and rectilinear ion traps[5]. Other approaches have involved microfabrication techniques with MEMS devices[6], micro-ion trap arrays[7,8], lab-on-a-chip designs[9], and patterned planar electrode ion traps in both the Paul trap[10] and toroidal trap[2] configurations. Our group has led the efforts in development of these planar electrode ion traps.

Planar electrode ion traps present several benefits. First, they only require the fabrication and alignment of two surfaces. This alignment requirement means that careful design and construction need only be done in two dimensions instead of three. Also, the electrodes are patterned onto the surfaces with lithographic processes. This results in a process that is less prone to surface roughness issues seen when miniaturizing machined electrodes. Another benefit is that planar electrode designs allow for trapping field adjustment and optimization after the trap has been fabricated and assembled. The planar electrode design allows for several different types of traps. As mentioned above, we have produced Paul traps and toroidal traps using this approach. In this work, we present a planar electrode linear ion trap.

Linear ion traps (LIT) have demonstrated superior performance to other quadrupole ion traps in several ways. They have been shown to have improved signal-to-noise ratio, increased trapping efficiency, increased trapping capacity, and increased resistance to deleterious space-charge effects[11,12]. These advantages make them effective as stand-alone mass spectrometers, or as part of a tandem setup with time-of-flight systems. Our planar electrode linear ion trap combines the advantages of linear ion traps with those of planar electrode ion traps.

The planar electrode LIT is implemented with two planar ceramic surfaces. These ceramic surfaces have lithographically patterned metal pairs of lines. The two patterned surfaces are arranged so that they face each other. Specific potentials are applied to each line pair to create a quadrupolar field. In our

planar electrode traps, the fields can be tuned after the system's original assembly. A great benefit of this is seen in field optimization and the analysis of higher order multipole effects. It has been demonstrated in previous works that deliberately adding a specific percentage of higher order multipoles into the field can actually improve mass spectrometer performance[13]. Our design of the planar electrode LIT allows easy tuning of deliberate higher order poles and compensation of undesired higher order poles.

2. Theoretical Discussion

A schematic of the planar electrode LIT surface is shown in Figure 1. Two of these surfaces are placed so that they face each other to form the ion trap. There is a central slit along the long axis of the trap for ion ejection. Specific voltages are applied to the symmetric line pairs to create the desired electric field. By adjusting the capacitive voltage divider circuit, subtle and precise adjustments can be made to the planar electrode LIT trapping fields. This versatility has allowed an experimental study on the effects of the higher order multipoles on trap performance.

The total trapping field potential in a 2-D ion trap is described by

$$\Phi(x,y) = \Phi_0(t) \sum_{N=0}^{\infty} A_N \Phi_N \quad (1)$$

where, A_N is the multipole expansion coefficient, and ϕ_N is the potential associated with a specific order of pole. Or in other words, the electric field is a summation of all the multipole components. In the planar electrode LIT, each symmetric pair of lines has its own values for the above equation. The total trapping field is a linear summation of the field of all line pairs. Fields were calculated using SIMION and Matlab. In SIMION, the electrode arrangement was setup so that only one pair of electrode lines was turned on to a maximum normalized voltage, and all other electrodes were grounded at 0 V. A neutral particle was then flown from one plate surface to the other, across the middle of the trapping region, to measure the field potential created by each line

pair. The coefficients for each line pair that correspond to the values for equation 1 are shown in table 1. The RF voltage for the line over the
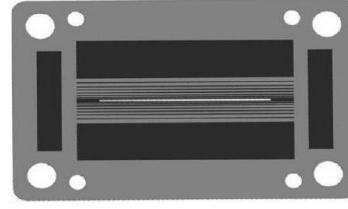

Figure 1: A schematic view of the electrode surface for the planar electrode LIT.

central slit was kept at 0 V for all parameters of our experiments. Figure 2 shows the equations of each line pair, giving a graphical representation of table 1.

Line	A0	A2	A4	A6
1	168.4429	18.4	-2.525	2.06
2	185.4522	-7.0538	-6.2327	0.8457
3	209.479	-34.6738	-3.8072	1.3366
4	108.4486	-25.6412	0.2638	0.567
5	48.3397	-12.2671	0.4456	0.2134

Table 1: Equations of electric potential for each line pair with line pair 1 being the inner line pair and pair 5 being the outer pair.

The quadrupole trapping field is created by picking the right coefficient by which to multiply each of the curves in table 1, and then adding up the results. These coefficients correspond to the specific voltages to apply to each line pair on the plate surface. This summation not only helps calculate the total trapping potential, but also the components of each higher order multipole. This is calculated by

(2)
$$A_2 = A_{21}\Phi_{01} + A_{22}\Phi_{02} + A_{23}\Phi_{03} + \cdots + A_{2m}\Phi_{0m}$$

(3)
$$A_4 = A_{41}\Phi_{01} + A_{42}\Phi_{02} + A_{43}\Phi_{03} + \cdots + A_{4m}\Phi_{0m}$$

(4)
$$A_6 = A_{61}\Phi_{01} + A_{62}\Phi_{02} + A_{63}\Phi_{03} + \cdots + A_{6m}\Phi_{0m}$$

where for A_{nm}, n is the multipole number (quadrupole, octopole, etc.), m is the line pair

numbered from the center slit, and where Φ_m is the RF amplitudes applied to line m.
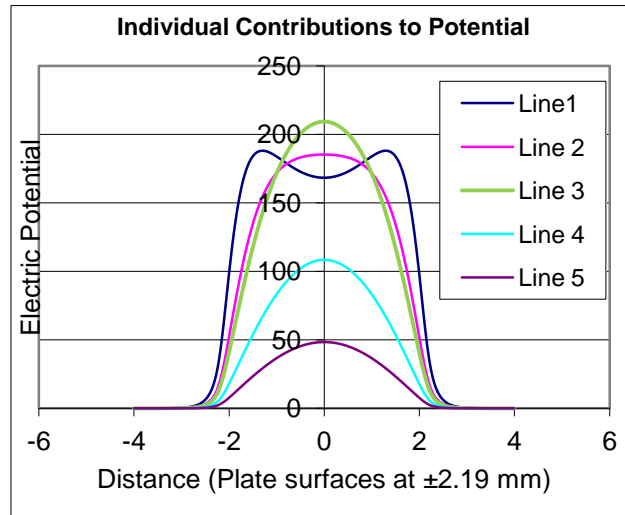

Individual Contributions to Potential

Figure 2: A plot showing the field profile of each line pair independent of other pairs.

1. Aluminum Oxide substrate

2. Laser drill holes for alignment and for vias. Fill vias with metal

3. Deposit gold on both sides of substrate

4. After spinning on photoresist, expose substrate to UV light through chrome mask.

5. Develop photoresist and etch gold to pattern on one side.

6. Repeat exposure and development on back side

7. Overcoat with germanium
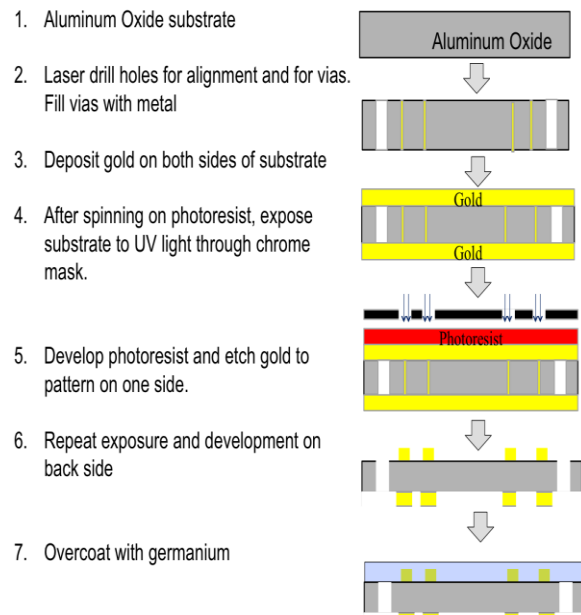
Figure 3: Steps for fabrication of planar electrode surfaces

3. Experimental Setup

The procedure for fabrication of the trapping plates is shown in Figure 3. Construction began with a 0.635mm thick, 99.6% pure alumina substrate (Hybrid-Tek, Clarksburg, NJ). A series of holes were then laser cut through the substrate. Some of these holes were cut for alignment purposes, some were for providing a path for ion ejection, and others were filled with gold to create vias for electrical contacts. The center ejection slit was cut to a width of 500μm. The gold filled vias were holes with a diameter of 125μm. The vias were placed symmetrically on either side of the slit and on either end of the slit. After laser cutting, the ceramic surfaces were polished to a surface roughness of better than 1 μm. Gold metal electrodes were patterned onto the substrate using photolithography in the Brigham Young University Integrated Microfabrication Laboratory. In the lithography process, photoresist was spun on the plate and patterned with chrome masks. The mask design for the trapping side of the plates contained one line to cover the entire ejection slit, four pairs of symmetric 25 μm wide lines about the slit, and one pair of outer lines that were several millimeters wide. After patterning the metal and removing the photoresist, a 100 nm layer of germanium was deposited on the trapping side of the substrates. The germanium layer coated the gold line electrodes to serves as a space charge dissipation layer for the trap. The resistivity of the germanium layer also produces a well-defined transition potential between adjacent lines, reducing edge effects on ions located close to the lines. The final plate surface, both before and after germanium deposition, is seen in Figure 4. The two wide bars on the edge of the plate are for axial confinement of ions in the trap. The voltage on these lines is set at 10 V.

Sapphire balls were placed in the alignment holes to provide a precise spacing between the two plate surfaces. A capacitive voltage divider circuit was setup onto a printed circuit board (PCB) to place the specific magnitudes of the radio frequency (RF) trapping field onto the desired line. The PCB made contact with the back side of the ceramic plates by way of gold, spring-loaded pogo pins. Figure 5 shows a schematic view of this assembly, while Figure 6 shows the PCBs and ceramic plates
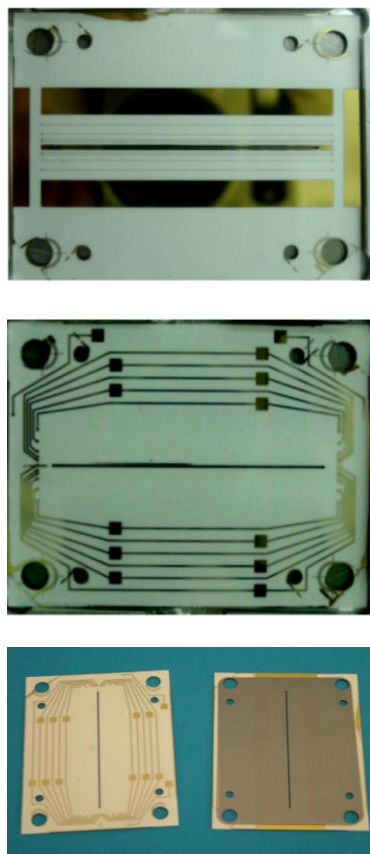
Figure 4: (top) Trapping side of LIT plates prior to germanium deposition, (middle) back side of plate for applying voltages to trapping surface, and (bottom) completed plate surface after germanium deposition.
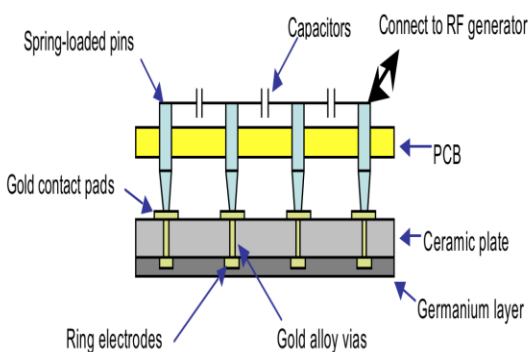

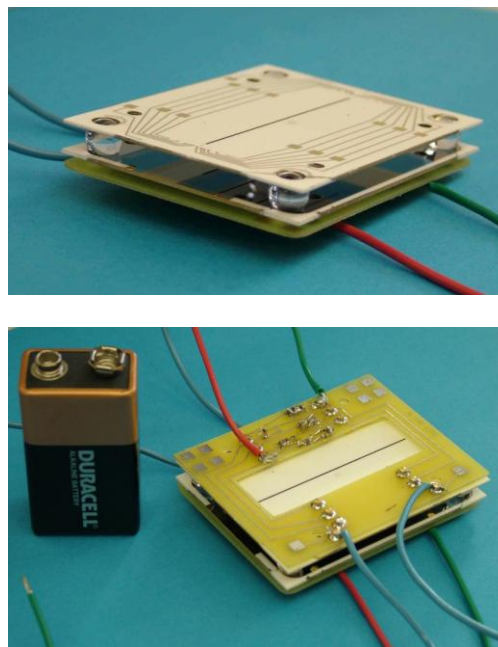**Figure 5: Schematic view of the PCB to trapping plate circuit**

Figure 6: Actual plate/PCB assembly

assembled together. The entire PCB and plate assembly was placed inside a copper box for shielding purposes. Custom electronics were built for controlling DC voltages for axial confinement, detector voltage supply, electron gun control, and electron gate control. An Ardara RF power supply (Ardara, PA) provided the trapping voltages applied to the PCB. The detector used was a continuous dynode electron multiplier by DeTech. The electron gun was placed to shoot electrons into the trapping area between the two plates down the long axis of the plates, birthing ions within the vicinity of the trapping region.

During a mass scan, the RF power supply was set at 720 V_{0-} at a frequency of 2.3 MHz. The RF power supply also had a DC offset of 3.5 V. An additional AC signal of 3.5 V was applied to the central line of one of the plates to cause resonant mass dependent ion ejection. The frequency of this resonant signal was swept from 100 kHz to 1.1 MHz over a time period of 100ms. Figure 7 demonstrates the timing of the RF, resonant ejection signal, and electron gun signals over the course of one scan. Sample gasses were leaked into the vacuum chamber at a pressure
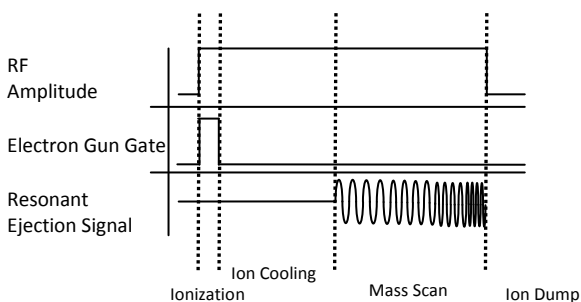
RF
Amplitude

Electron Gun Gate

Resonant
Ejection Signal

Ionization Ion Cooling Mass Scan Ion Dump

Figure 7: A diagram showing the timing of various control signals of the LIT system.

of $2*10^{-6}$ torr with a background helium buffer gas also leaked in at a pressure of $2*10^{-5}$ torr.

4. Results

A mass spectrum was obtained for isobutylbenzene using a frequency sweep. This spectrum is shown in Figure 8. Mass assignments were made by comparing the RF amplitude, frequency, and the frequency of the resonant ejection signal at the time a peak signal appeared during the mass scan to standard quadrupolar ion trap theory. The spectrum measured under these conditions exhibits good signal-noise-ratio and exhibits near unit resolution using the FWHM for several of the peaks, especially for the mass 51 peak.

The signal was verified to contain mass peaks by altering the frequency scan range of the experiment, and by varying the pressure of the sample. Figure 9 shows a slight shift in the peak position on a mass spectrum of isobutylbenzene with respect to the scan
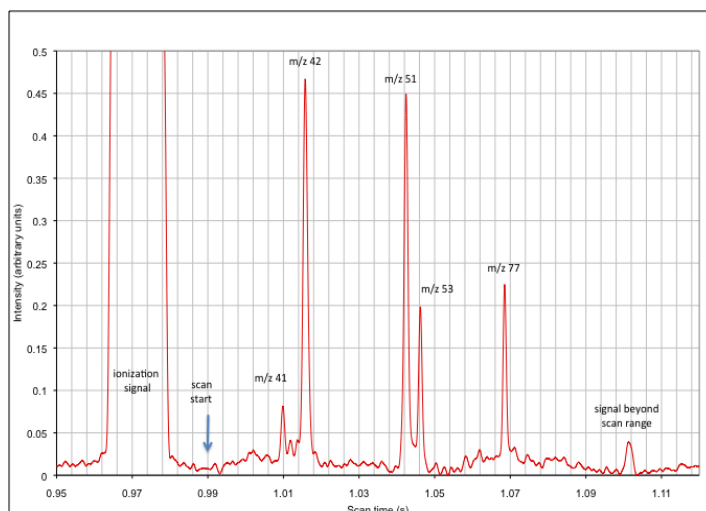

Figure 8: Spectrum of isobutylbenzene taken from the planar electrode LIT.

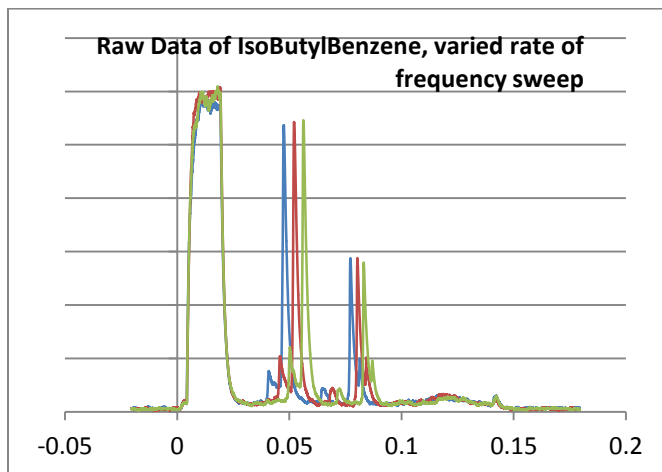Raw Data of IsoButylBenzene, varied rate of frequency sweep

Figure 9: Scan data showing mass peak shifts with a shift in frequency on the resonant ejection signal. Each data series represents a scan with a slightly varied frequency range during the mass scan.

time with subtle adjustments in the frequency range of the scan. This verifies that a peak occurs at a specific frequency on the resonant ejection signal. Figure 10 shows how with decreased sample pressure, resolution of mass peaks improves.

The values of the A_4/A_2 and A_6/A_2 terms used in this experiment are 0.803% and -2.67% respectively. The goal of this particular field design

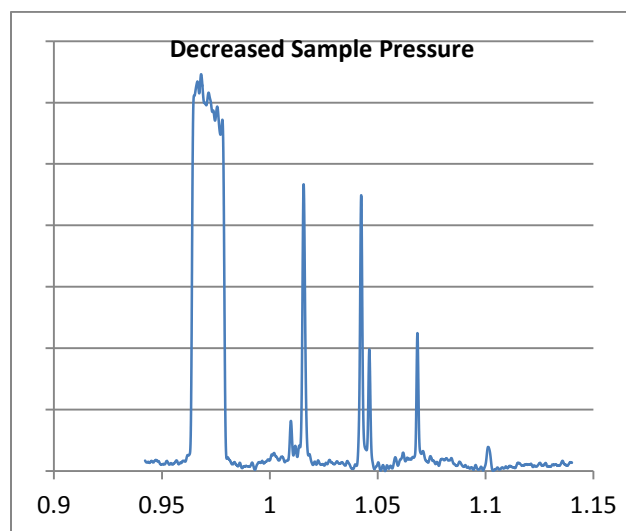Original Data from Frequency Comparison
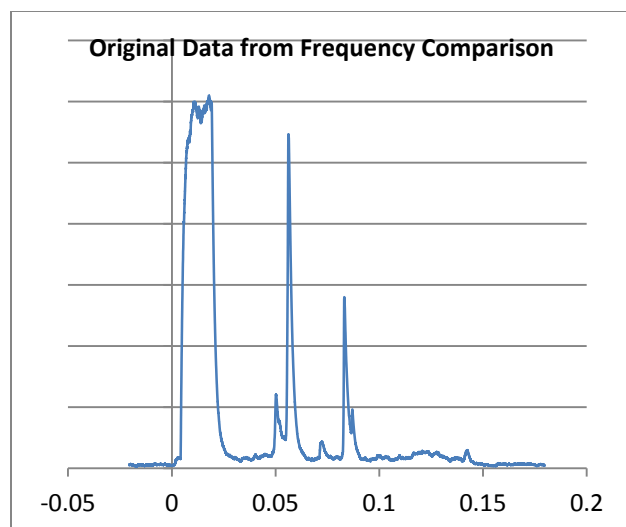

Decreased Sample Pressure

Figure 10: A mass spectrum showing the effects of changing the sample pressure in the vacuum chamber.

was to create a field that was as purely quadrupolar as possible. Additional improvement to spectrum resolution and mass range is expected as improvements are made both in electric field profile and in the integrity of our vacuum system.

5. Conclusion

We have demonstrated the implementation of a linear type ion trap using patterned planar electrodes. We have near unit mass resolution on the mass range of 30-80 mass units using isobutylbenzene as a test sample. By these results, we have shown the viability of the planar electrode LIT. The microfabrication approach to making the LIT lends itself well to miniaturization. In addition to exploring miniaturization of this trap, in the future, we will refine performance of this trap by experimenting with the values of the higher order multipole in the trapping field. Additional work will also be directed to examining the electrode layout of the plate to find a more optimal design.

References

1. Surface-Electrode Architecture For Ion-Trap Quantum Information Processing, J. Chiaverini, R. B. Blakestad, J. Britton, J. D. Jost, C. Langer, D. Leibried, R. Ozeri, and D. J. Wineland, Quantum Information and Computation, Vol. 5, No. 6 (2005) 419–439
2. Halo Ion Trap Mass Spectrometer, Daniel E. Austin, Miao Wang, Samuel E. Tolley, Jeffrey D. Maas, Aaron R. Hawkins, Alan L. Rockwood, H. Dennis Tolley, Edgar D. Lee, and Milton L. Lee, Anal. Chem. 2007, 79, 2927-2932
3. Handheld Rectilinear Ion Trap Mass Spectrometer, Liang Gao, Qingyu Song, Garth E. Patterson, R. Graham Cooks, and Zheng Ouyang, Anal. Chem. 2006, 78, 5994-6002
4. A compact, high-resolution Paul ion trap mass spectrometer with electron-impact ionization, O. J. Orient and A. Chutjian, REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 5 MAY 2002
5. Novel Linear Ion Trap Mass Analyzer Composed of Four Planar Electrodes,Z. Ouyang, G.Wu, Y. Song, H. Li,W.R. Plass, R.G. Cooks, Analytical Chemistry 76 (2004) 4595
6. Planar ion trap geometry for microfabrication, M.J. Madsen,_W.K. hensinger, D. Stick, J.A. Rabchuk, C. Monroe, Appl. Phys. B 78, 639–651 (2004)
7. Towards the hand-held mass spectrometer: design considerations, simulation, and fabrication of micrometer-scaled cylindrical ion

traps, Matthew G. Blain, Leah S. Riter, Dolores Cruz, Daniel E. Austin, Guangxiang Wu, Wolfgang R. Plass, R. Graham Cooks, International Journal of Mass Spectrometry 236 (2004) 91–104

8. Simulations of Ion Trapping in a Micrometer-Sized Cylindrical Ion Trap, Daniel E. Austin, Dolores Cruz and Matthew G. Blain, J Am Soc Mass Spectrom. 2006 Mar;17(3):430-41

9. Ion Trap in a Semiconductor Chip, D. Stick, W. K. Hensinger, S. Olmschenk, M. J. Madsen, K. Schwab, and C. Monroe, *Nature Physics* 2, 36 - 39 (2006)

10. Novel Ion Traps Using Planar ResistiveElectrodes: Implications for Miniaturized Mass Analyzers, D. E. Austin, Y. Peng, B. J. Hansen, I. W. Miller, A. L. Rockwood, A. R.Hawkins, and S. E. Tolley, J. Am. Soc. Mass Spectrom. 19, 1435 2008

11. A New Linear Ion Trap Mass Spectrometer, James W. Hager, Rapid Communications in Mass Spectrometry, 2002, Number 16

12. A Two-Dimensional Quadrupole Ion Trap Mass Spectrometer, Jae C. Schwartz, Michael W. Senko, and John E. P. Syka, Journal of the American Society for Mass Spectrometry, 2002, Volume 13, Issue 6

13. Co-occurrence of Boundary and ResonanceEjection in a Multiplexed Rectilinear Ion Trap Mass Spectrometer, Amy M. Tabert, Michael P. Goodwin, and R. Graham Cooks, Journal of the American Society of Mass Spectrometry 2006, Number 17