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RESEARCH ARTICLE

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A Microscale Planar Linear Ion Trap Mass Spectrometer

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Abstract. The planar linear ion trap (PLIT) is a version of the two-dimensional linear quadrupole ion trap constructed using two facing dielectric substrates on which electrodes are lithographically patterned. In this article, we present a PLIT that was successfully miniaturized from a radius of 2.5 mm to a microscale radius of 800 µm (a scaling factor of 3.125). The mathematics concerning scaling an ion trap mass spectrometer are demonstrated—including the tradeoff be-

tween RF power and pseudopotential well depth. The time average power for the microscale PLIT is, at best, ~ 1/ 100 that of the PLIT but at a cost of potential well depth of ~ 1/10 the original. Experimental data using toluene/ deuterated toluene and isobutylbenze to verify trap performance demonstrated resolutions around 1.5 Da at a pressure of 5.4×10^{-3} Torr. The microscale PLIT was shown to retain resolutions between 2.3 and 2.7 Da at pressures up to 42×10^{-3} Torr while consuming a factor of 3.38 less time average power than the unscaled PLIT. Keywords: Mass spectrometry, Ion trap miniaturization, Ion traps, Instrumentation

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Introduction

adio frequency (RF) ion traps based on the quadrupole R device developed by Paul and Steinwedel utilize a dynamic electric field to spatially confine the trajectory of charged particles and may be employed as mass spectrometers by selectively ejecting trapped molecules based on the mass to charge ratio [1-7]. Because of the inherent sensitivity and specificity of this process, ion trap mass spectrometers have become a popular scientific instrument with applications in space exploration [8], clinical diagnostics [9, 10], and agriculture [11]. In the past two decades, there has been a push to develop portable ion trap mass spectrometers for in situ mass analysis by geometrically scaling traps to smaller sizes [12-16]. This decreases the power and vacuum requirements which allows field portable instruments to use smaller/less powerful vacuum pumps and batteries. It should also be noted that other types of mass analyzers, such as magnetic [17], capillary electrophoresis [18], and time-of-flight [19, 20], have also investigated miniaturization.

Multiple varieties of RF ion traps consisting of machined components have been miniaturized. Patterson et al. of the Cooks' research group developed miniaturized cylindrical and rectilinear traps [21-24], Lammert et al. built a miniature toroidal trap [25], and Brinkerhoff et al. designed a miniature quadrupole mass analyzer for the ExoMars 2018 Rover [26]. However, in order to achieve sub-millimeter (microscale) radii, several research teams have deviated from the traditional machining methods and trap configurations, with the marked exception of Kornienko et al. of the Ramsey group [27], specifically through the utilization of microfabrication processes. For example, Wright et al. miniaturized a triple quadrupole mass spectrometer [28] based on the microengineered quadrupole filter of Malcolm et al. [29] using microelectromechanical system (MEMS) techniques. Chaudhary et al. [30] and Fox et al. [31] also used MEMS techniques to develop a large array of cylindrical traps and a coaxial ring ion trap, respectively. Geear et al. used deep silicon etching for a quadrupole ion trap [32]. Pau et al. developed a single planar technique using microfabrication processes for a toroidal trap [33].

In this article, we present a miniaturized coplanar trap, the microscale planar linear ion trap (μ PLIT), that was successfully miniaturized to an r_0 of 800 μ m with electrodes 20- μ m wide using

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microfabrication processes. First, the mathematics concerning scaling an ion trap mass spectrometer—including the effects on power, pseudopotential well depth, and pressure—are demonstrated. Then, the μ PLIT electrode layout and fabrication procedure are presented. Finally, empirical results are presented that depict the outcome of the miniaturization including peak resolution, time average power, and pressure viability.

Background

Scaling an Ion Trap Mass Analyzer

Ion trap mass spectrometer miniaturization for decreased RF power requirements is an exercise in trapping parameter manipulation. According to Douglas et al. [34], the q value for a linear ion trap derived from the Matthieu equation is defined by:

$$q_{\rm x} = -q_{\rm y} = \frac{4\mathrm{eV}}{\mathrm{mr}_{\rm o}^2 \Omega^2} \tag{1}$$

where *e* is the charge of the ion, *V* is the zero-to-peak voltage of the applied RF, *m* is the molecular mass of the particle in kilograms, r_0 is the radius from the central axis to the electrodes in meters, and Ω is the frequency of the RF [34–36]. Now, to develop a generalized format for trap miniaturization, let us assume an arbitrary scaling factor α to r_0 such that:

$$r_{\rm o2} = \frac{r_{\rm o1}}{\alpha_0} \tag{2}$$

where the subscript 2 refers to the scaled/miniaturized trap and 1 to the original. With some algebra, applying Eq. (2) to Eq. (1) yields $q_{x2} = \alpha_0^2 q_{x1}$. Here, we see that, when miniaturizing a trap, the qvalue for an arbitrary ion increases by the square of the change in r_0 . As Tian et al. illustrated, either V or Ω , or a combination of both, can be adjusted to retain the same m/z range of masses or qvalue for a specific ion [37]. By assigning α_1 as a scaling factor for V and α_2 for Ω , the equation for q_{x2} can be represented as:

$$q_{x2} = \frac{4e(V_1/\alpha_1)}{m(r_{01}/\alpha_0)^2(\alpha_2\Omega_1)^2} = \frac{\alpha_0^2}{\alpha_1\alpha_2^2}q_{x1}.$$
(3)

So, to cover the same range of m/z as the original trap, $\alpha_0^2/(\alpha_1 \alpha_2^2)$ should be approximately equal to 1.

One of the dominant motivations for miniaturizing an ion trap for handheld portable applications is the decreased RF power consumption that accompanies the scaled RF voltage amplitude [23, 38–40]. Actually calculating the power required to drive an ion trap is complicated and is dependent on the specific RF generator being used. For simplicity, let us instead evaluate the time average power of a signal and then assume, to the first order, that it is linearly proportional to the total drive power. The time average power of a signal is given by:

$$P_{\rm AVG} = \frac{V^2}{2Z} \tag{4}$$

where V is the voltage amplitude and Z is the impedance [41]. For a strictly capacitive trap, $Z= 1/(i\Omega C)$ where C is the equivalent capacitance of the trap and Ω is the RF frequency. By applying the scaling factors from Eq. (3) to Eq. (4), the time average power of a miniaturized trap is:

$$P_{\rm AVG2} = \frac{(V_1/\alpha_1)^2}{2(Z_1/[\alpha_2\alpha_{\rm C}])} = \frac{\alpha_2\alpha_{\rm C}}{\alpha_1^2}P_{\rm AVG1} = \frac{P_{\rm AVG1}}{\alpha_3}.$$
 (5)

where $\alpha_{\rm C}$ is the scaling factor for the capacitance such that $C_2 = \alpha_{\rm C}C_1$ and where $\alpha_3 = \alpha_1^2/(\alpha_2\alpha_{\rm C})$. By assuming that the drive power is linearly proportional to the time average power (to the first order), we can label α_3 as the power scaling coefficient.

From Eqs. (4) and (5), it is obvious that scaling the RF voltage amplitude will have the largest effect on the time average power. However, it should be noted that $\alpha_{\rm C}$ is not related to the trapping parameters in Eq. (1), rather to the type of trap being used (e.g., machined, microfabricated, PCB). Some traps may suffer from an $\alpha_{\rm C}$ > 1 when miniaturized which may actually increase the time average power. For the planar linear ion trap discussed in this article, the capacitance is determined by an external capacitor network, so $\alpha_{\rm C}$ = 1. In this case, for a maximum reduction in the time average power, α_1 (the RF voltage amplitude scaling coefficient) should equal α_0^2 and α_2 (the RF frequency scaling coefficient) should equal 1 such that $\alpha_3 = \alpha_0^4$. For the µPLIT where $\alpha_0 = 3.125$, $\alpha_3 \approx 95.4$ or $P_{\rm AVG2} \approx 0.01 P_{\rm AVG1}$ which is a considerable reduction in time average power.

However, it should be noted that scaling V by $1/\alpha_0^2$ is not always desirable. This is best illustrated by the pseudopotential well model as derived by Dehmelt [42] which, according to March [3, 5], defines the maximum kinetic energy that an externally generated ion may possess and still be trapped [4]. The pseudopotential well depth is given by the equation:

$$\overline{D}_{\rm x} = \frac{1}{8} q_{\rm x} {\rm V}. \tag{6}$$

Applying the same scaling factors used in Eqs. (3) and (5) yields the relationship for the pseudopotential well depth:

$$\overline{D}_{x2} = \frac{1}{8} q_{x2} V_2 = \frac{1}{8} \left(\frac{a_0^2}{\alpha_1 \alpha_2^2} q_{x1} \right) \left(\frac{V_1}{\alpha_1} \right) = \left(\frac{a_0}{\alpha_1 \alpha_2} \right)^2 \overline{D}_{x1}.$$
 (7)

Considering the earlier example where $\alpha_1 = \alpha_0^2$ resulting in $\alpha_3 \approx 95.4$, the pseudopotential well depth of the scaled is $\overline{D}_{x2} \approx 0.1 \overline{D}_{x1}$ —this is obviously not desirable. As a result, both - *V* and Ω were adjusted for the µPLIT in order to reduce the time average power but retain some depth in the pseudopotential well as mentioned by Tian et al. [37] and observed by Kornienko et al. [27]. The final scaling results and factors for the µPLIT are discussed in "Experiment and Results."

An added benefit for miniaturized traps is the ability to operate at higher pressures as demonstrated by the Ramsey research group in their articles concerning high-pressure mass spectrometry [43-45]. This is imperative for portable



Figure 1. A comparison of the planar linear ion trap (PLIT) with $r_0 = 2.5 \text{ mm}$ (a) and $r_0 = 2.5 \text{ µm}$ (b). A drawn-to-scale image (electrode height exaggerated) cross-sectional image of the microscale PLIT with the electrodes numbered (c) and a SIMION simulation of the PLIT quadrupolar potential (d)

applications by allowing the use of smaller, less powerful vacuum pumps [39, 46, 47]. Unfortunately, literature relating trap size, pressure, and performance is limited. Xu et al. do indicate that the overall effectiveness of an RF device at higher pressures depends on a balance between the electric field and ion-neutral collisions [48]. This balance, according to Xu et al., is related to the mean free path of an ion in a buffer gas. From this viewpoint, it could be argued that in miniaturized traps the mean free path can be shorter (or, inversely, the background pressure can be higher) due to the tighter geometry. This would explain the results from the Ramsey group mentioned above. However, more conclusive findings outside the scope of this article are needed to fully prove such a theory.

Planar Linear Ion Trap

The planar linear ion trap (PLIT) is a two-dimensional quadrupole ion trap inspired by the linear ion trap developed by Syka et al. at Thermo Electronic [49–51]. However, unlike more traditional traps that use machined components, the PLIT is constructed using two facing dielectric substrates on which electrodes are lithographically patterned to resemble a linear ion trap. A quadrupolar trapping region is created by applying an RF distribution to the electrodes. This coplanar method was also used to create planar Paul, toroidal, and coaxial traps [12, 52–54].

This article focuses on scaling the PLIT to a microscale r_0 of 800 µm from the PLIT developed by Tian et al. [55] which used an r_0 of 2.5 mm thus giving a scaling factor α from Eq. (2) of 3.125. For the µPLIT, ceramic wafer substrates were manufactured by Aremco (Valley Cottage, NY) which included a scaled tapered ejection slit [56] approximately 166-µm wide on the trapping side as seen in Figure 1c. It should be noted that the electrode pattern for the $r_0 = 2.5$ mm geometry requires a 500-µm wide ejection slit. Using physical vapor deposition (PVD), a 1- to 2-µm-thick layer of aluminum was deposited. The aluminum layer was then lithographically patterned and etched to form the electrode pattern shown in Figure 1a and b with the widths/positions in Table 1. Afterward, the ceramic substrates were diced into a rectangular plate. One hundred nanometers of germanium was then deposited using PVD over the patterned electrodes to cover the dielectric substrate and act as a resistive layer between the electrodes. After gluing each plate to a custom-printed circuit board (PCB) (Ouick Turn Circuits, Salt Lake City, UT), the electrodes were connected to the PCB via wire bonds. To create the quadrupolar trapping region, two µPLIT halves are placed facing one another and a capacitor network PCB interfaces to the backside of the µPLIT PCB to create the RF distribution seen in Table 1 [54, 56]. The capacitor network has an equivalent capacitance of 24 pF (which is much larger than the femtofarad range

Table 1. Electrode Geometry, Spacing, and Voltage Distribution

Electrode number from center	Electrode width $(r_0 = 2.5 \text{ mm})$	Electrode width (r_0 = 800 µm)	Distance from ejection slit (r_0 = 2.5 mm)	Distance from ejection slit (r_0 = 800 µm)	RF voltage amplitude percentage
5	4500 μm	1500 μm	7.75 mm	2.58 mm	100
4	50 μm	20 μm	3.79 mm	1.263 mm	100
3	50 μm	20 µm	2.19 mm	0.73 mm	14
2	50 μm	20 µm	1.26 mm	0.42 mm	14
1	50 μm	20 µm	0.91 mm	0.30 mm	0
0	800 µm	330 µm	0 mm	0 mm	0



Figure 2. A spectrum of isobutylbenzene showing the m/2 91/ 92 and m/2 134 peaks using the $\beta = 2/3$ hexapole resonance line

capacitance between the electrode traces) for both the μ PLIT and unscaled PLIT such that α_C = 1.

Experiment and Results

Following fabrication, the μ PLIT was placed in a vacuum chamber which was pumped down to a high vacuum around 0.5×10^{-6} Torr. Then, using a leak valve (Granville Phillips, Boulder, CO, USA), sample vapor was introduced to the vacuum for a stable pressure between 1 and 3×10^{-6} Torr. Helium was then added to the chamber for a final pressure of 5.4×10^{-3} Torr.

The electronic timing of each scan was very similar to that of previously published experiments using a PLIT [55, 57]. Ionization was 20 ms at 72 V_{0-p} for Figure 2 and 86 V_{0-p} for Figure 3 which was followed by a 10-ms cooling period. The RF amplitude was then ramped for 40 ms from 72 to 133 V_{0-p} for Figure 2 and 86 to 111 V_{0-p} for Figure 3. The RF frequency was 2.71 MHz. An additional positive DC offset of 5 V was added to the end bars seen in Figure 1 to contain the ions axially. Ions were resonantly ejected using phase tracking circuitry [58]. The best resolutions were obtained using the $\beta = 2/3$ hexapole resonance line as seen in the isobutylbenzene



Figure 3. A spectrum showing the *m/z* 91/92 peaks of toluene and 98/100 of deuterated toluene using the resonance for β = 0.92 enhanced boundary ejection

 Table 2. A Comparison of the Scaled and Unscaled PLIT

	<i>r</i> _o (mm)	$\Omega \left(\mathrm{MHz} \right)$	V (V 0-Peak)	Calculated time average power (W)
PLIT µPLIT (Figure 2)	2.5 0.8	1.35 2.71	200-560 86-111 x = 2.22 (min)	4.04 1.51 r = 2.60 (min)
uPLIT (Figure 3)	$a_0 = 3.123$ 0.8 $a_0 = 3.125$	$a_1 = 2.01$ 2.71 $a_1 = 2.01$	$a_2 = 2.33$ (min) 72-133 $a_2 = 2.78$ (min)	$a_3 = 2.69$ (min) 1.19 $a_3 = 3.38$ (min)

spectrum in Figure 2 with an AC frequency of 883.3 kHz, a voltage amplitude of 0.55 V, a phase of 0°, and a small DC offset to the AC of 0.55 V. For comparison to previously published data, the β =0.92 resonance was also interrogated for a 1:1 toluene/d-8 toluene mixture, as shown in Figure 3, with an AC frequency of 1.248 MHz, a voltage amplitude of 0.4 V, a phase of 0°, and a small DC offset to the AC of 0.2 V. Each recorded spectrum was an average of 20 individual scans.

Because miniaturized traps suffer from increased space charge effects, which according to March and Todd [5] widen and shift mass peaks, the resolution of the μ PLIT is worse than the unscaled PLIT where resolutions around 0.5 Da were achieved [55]. In Figure 2, the *m/z* 91/92 and *m/z* 134 exhibited resolutions of about 2.3, 1.3, and 3.2 Da respectively (calculated using a Gaussian peak model). In Figure 3, the *m/z* 91/92 and *m/z* 98/100 had resolutions around 1.5 Da, 1.4 Da, 2.7 Da, and 1.5 Da, respectively (also calculated with a Gaussian peak model). Although the resolution is significantly degraded from the unscaled PLIT [55], a mass resolution of a few daltons can still yield useful information in portable mass spectrometer applications.

A comparison of the μ PLIT trapping parameters to the original PLIT indicates that the μ PLIT was scaled correctly. Table 2 is a comparison of the two designs including the scaling factors for toluene/d-8 toluene spectra (like in Figure 3). It should be noted that since the μ PLIT and unscaled PLIT utilize an external capacitor network, the trap capacitance is approximately the same (i.e., $\alpha_C = 1$). Using the scaling factors in Table 2 in Eq. (3), the new q_{x2} value is rounded to 1.04q_{x1}—an indication that the μ PLIT was indeed operating



Figure 4. The maximum peak intensity of the m/z 91/92 peaks of the toluene sample are shown versus total pressure



Figure 5. A collection showing an expanded view of the spectra that make up Figure 4 of toluene and d-8 toluene with m/z 91/92 and m/z 98/100. The x-axis for each subplot is time and the y-axis is intensity in arbitrary units

around the same mass range as the previously published results [55]. The power requirements of the trap were also reduced by a minimum factor of 2.69 for Figure 2 and 3.38 for Figure 3 as calculated using Eq. (4).

The µPLIT behavior versus gas pressure was investigated by slowly changing the background helium pressure periodically beginning with 2.5×10^{-3} Torr up to 42×10^{-3} Torr. The RF and sample pressure of 1:1 toluene:d-8 toluene remained unchanged, but the AC resonance amplitude was increased periodically to compensate for the higher pressures (this was also observed by Song et al. [46]). Figure 4 graphically represents the maximum peak intensity of the m/z 91/92 peak. The increase in amplitude at 10.7×10^{-3} Torr and 17.2×10^{-3} Torr correspond to increasing the AC amplitude to 0.65 and 0.7 V, respectively. The AC amplitude was adjusted for almost every sample after that culminating with 0.95 V for the final spectrum at 42×10^{-3} Torr. The increase in the mass spectral intensity over pressure follows trends observed by other researchers such as Todd et al. [59].

Figure 5 is simply a collection of spectra that make up Figure 4 that indicate changes in behavior of the μ PLIT. A total pressure of 5.4×10^{-3} Torr gave the best resolution with well-separated *m/z* 98 and 100 peaks in the deuterated toluene. The shoulder of the *m/z* 92 was also visible at lower pressures. By 16.6×10^{-3} Torr, the *m/z* 91/92 peak did not exhibit a shoulder, and by 42×10^{-3} Torr, the *m/z* 98/100 peaks were essentially fully combined for a final resolution between 2.3 and 2.7 Da estimated using a Gaussian peak model. As mentioned before, since resolutions of a few daltons are acceptable for portable mass spectrometry applications, 2.3–2.7 Da is acceptable. The decrease in resolution over pressure was expected based on models/results from Whitten et al. [60] and Xu et al. [48] The optimal pressure for resolution in the unscaled PLIT ranged between 3 and 4×10^{-3} Torr whereas the $\mu PLIT$ ranged between 5 and 8×10^{-3} Torr.

Remaining Challenges

There are two main considerations for further miniaturization of the PLIT: the tapered ion ejection slit and the cross-sectional aspect ratio. The tapered ion ejection slit is a concern because finding a manufacturer that could reliably machine a 45° taper with a 166-µm wide opening roughly 1.5-cm long required switching the substrate from glass to ceramic [56]. Substrates designed for radii smaller than the µPLIT may require a different fabrication method, such as a custom ceramic mold casting, to ensure a consistent, defect-free, tapered slit. The narrow aspect ratio seen in Figure 1 may also be troublesome for the sake of populating the trap with externally generated ions. Future setups may require internally generated ions or externally generated ions that are directed toward the trap aperture.

Conclusions

The planar linear ion trap (PLIT) was successfully miniaturized to a microscale r_o and can potentially be used as a portable mass spectrometer. This was done by redesigning the electrodes on the PLIT surface to have an r_o of 800 µm. The RF voltage amplitude and frequency were scaled to compensate for the smaller r_o . The µPLIT successfully confined then resonantly ejected ions with resolutions of approximately 2–3 Da. The performance of the µPLIT was also tested over a range of pressures from 2.5 to 42×10^{-3} Torr and retained resolutions between 2.3 and 2.7 Da. Ultimately, the µPLIT was shown to retain resolutions viable for portable mass spectrometry at pressures in the tens of millitorr while consuming a factor of 3.38 less time average power than the unscaled PLIT.

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References

- Cooks, R.G., Kaiser, R.E.: Quadrupole ion trap mass spectrometry. Acc. Chem. Res. 23, 213–219 (1990)
- Holzscheiter, M.H.: A brief history in time of ion traps and their achievements in science. Phys. Scr. **T59**, 69–76 (1995)
- March, R.E.: An introduction to quadrupole ion trap mass spectrometry. J. Mass Spectrom. 32, 351–369 (1997)
- March, R. E. In *Encyclopedia of Analytical Chemistry*, Meyers, R. A., Ed.; John Wiley & Sons Ltd: Chichester, UK, 2000, pp 11848–11871
- March, R.E., Todd, J.F.J.: Quadrupole Ion Trap Mass Septrometry. John Wiley & Sons, Inc., Hoboken, New Jersey (2005)
- Pedder, R. E. Fundamental Studies in Quadrupole Ion Trap Mass Spectrometry. dissertation, University of Florida1992
- Paul, W., Steinwedel, H.: Notizen: Ein neues Massenspektrometer ohne Magnetfeld. Zeitschrift f
 ür Naturforschung A. 8, (1953)
- Palmer, P.T., Limero, T.F.: Mass spectrometry in the U.S. space program: past, present, and future. J. Am. Soc. Mass Spectrom. 12, 656–675 (2001)
- 9. Ye, H., Gemperline, E., Li, L.: A vision for better health: mass spectrometry imaging for clinical diagnostics. Clin. Chim. Acta. **420**, 11–22 (2013)
- Li, L.F., Chen, T.C., Ren, Y., Hendricks, P.I., Cooks, R.G., Ouyang, Z.: Mini 12, miniature mass spectrometer for clinical and other applications—introduction and characterization. Anal. Chem. 86, 2909– 2916 (2014)
- Laturnus, F., Grøn, C.: Organic waste products in agriculture—monitoring the waste constituents phthalate esters in soil-crop system by gas chromatography and ion trap tandem mass spectrometry. J. Environ. Eng. Landsc. Manag. 15, 253–260 (2007)
- Austin, D.E., Peng, Y., Hansen, B.J., Miller, I.W., Rockwood, A.L., Hawkins, A.R., Tolley, S.E.: Novel ion traps using planar resistive electrodes: implications for miniaturized mass analyzers. J. Am. Soc. Mass Spectrom. 19, 1435–1441 (2008)
- Li, A., Hansen, B.J., Powell, A.T., Hawkins, A.R., Austin, D.E.: Miniaturization of a planar-electrode linear ion trap mass spectrometer. Rapid Commun. Mass Spectrom. 28, 1338–1344 (2014)
- Derkits, D., Wiseman, A., Snead, R.F., Dows, M., Harge, J., Lamp, J.A., Gronert, S.: Development and evaluation of a variable-temperature quadrupole ion trap mass spectrometer. J. Am. Soc. Mass Spectrom. 27, 339– 343 (2016)
- Taylor, N., Austin, D.E.: A simplified toroidal ion trap mass analyzer. Int. J. Mass Spectrom. Ion Process. 321-322, 25–32 (2012)
- Wu, Q., Li, A., Tian, Y., Zare, R.N., Austin, D.E.: Miniaturized linear wire ion trap mass analyzer. Anal. Chem. 88, 7800–7806 (2016)
- Sinha, M.P., Tomassian, A.D.: Development of a miniaturized, lightweight magnetic sector for a field-portable mass spectrograph. Rev Sci Instrum. 62, 2618–2620 (1991)
- He, M.Y., Xue, Z.H., Zhang, Y.N., Huang, Z.J., Fang, X., Qu, F., Ouyang, Z., Xu, W.: Development and characterizations of a miniature capillary electrophoresis mass spectrometry system. Anal. Chem. 87, 2236–2241 (2015)
- Bryden, W.A., Benson, R.C., Ecelberger, S.A., Phillips, T.E., Cotter, R.J., Fenselau, C.: The tiny-TOF mass spectrometer for chemical and biological sensing *Johns Hopkins APL Technol.* Dig. 16, 296–310 (1995)
- Getty, S.A., Brinckerhoff, W.B., Cornish, T., Ecelberger, S., Floyd, M.: Compact two-step laser time-of-flight mass spectrometer for in situ analyses of aromatic organics on planetary missions. Rapid Commun. Mass Spectrom. 26, 2786–2790 (2012)
- Patterson, G.E., Guymon, A.J., Riter, L.S., Everly, M., Griep-Raming, J., Laughlin, B.C., Ouyang, Z., Cooks, R.G.: Miniature cylindrical ion trap mass spectrometer. Anal. Chem. 74, 6145–6153 (2002)
- Badman, E.R., Cooks, R.G.: A parallel miniature cylindrical ion trap array. Anal. Chem. 72, 3291–3297 (2000)

- Gao, L., Song, Q., Patterson, G.E., Cooks, R.G., Ouyang, Z.: Handheld rectilinear ion trap mass spectrometer. Anal. Chem. 78, 5994–6002 (2006)
- Fico, M., Maas, J.D., Smith, S.A., Costa, A.B., Ouyang, Z., Chappell, W.J., Cooks, R.G.: Circular arrays of polymer-based miniature rectilinear ion traps. Analyst. 134, 1338–1347 (2009)
- Lammert, S.A., Rockwood, A.A., Wang, M., Lee, M.L., Lee, E.D., Tolley, S.E., Oliphant, J.R., Jones, J.L., Waite, R.W.: Miniature toroidal radio frequency ion trap mass analyzer. J. Am. Soc. Mass Spectrom. 17, 916–922 (2006)
- Brinckerhoff, W.B., Pinnick, V.T., van Amerom, F.H.W., Danell, R.M., Arevalo, R.D., Atanassova, M.S., Xiang, L., Mahaffy, P.R., Cotter, R.J., Goesmann, F., Steininger, H.: IEEE Aerospace Conference. 2013, 1–8 (2013)
- Kornienko, O., Reilly, P.T.A., Whitten, W.B., Ramsey, J.M.: Micro ion trap mass spectrometry. Rapid Commun. Mass Spectrom. 13, 50–53 (1999)
- Wright, S., Malcolm, A., Wright, C., O'Prey, S., Crichton, E., Dash, N., Moseley, R.W., Zaczek, W., Edwards, P., Fussell, R.J., Syms, R.R.: A microelectromechanical systems-enabled, miniature triple quadrupole mass spectrometer. *Anal Chem.* 87, 3115–3122 (2015)
- Malcolm, A., Wright, S., Syms, R.R., Dash, N., Schwab, M.A., Finlay, A.: Miniature mass spectrometer systems based on a microengineered quadrupole filter. Anal. Chem. 82, 1751–1758 (2010)
- Chaudhary, A., van Amerom, F., Short, R.T.: Development of microfabricated cylindrical ion trap mass spectrometer arrays. J. Microelectromech. Syst. 18, 442–448 (2009)
- Fox, J., Saini, R., Tsui, K., Verbeck, G.: Microelectromechanical system assembled ion optics: an advance to miniaturization and assembly of electron and ion optics. Rev Sci Instrum. 80, 093302 (2009)
- Geear, M., Syms, R.R.A., Wright, S., Holmes, A.S.: Monolithic MEMS quadrupole mass spectrometers by deep silicon etching. J. Microelectromech. Syst. 14, 1156–1166 (2005)
- Pau, S., Whitten, W.B., Ramsey, J.M.: Planar geometry for trapping and separating ions and charged particles. Anal. Chem. 79, 6857–6861 (2007)
- Douglas, D.J., Frank, A.J., Mao, D.: Linear ion traps in mass spectrometry. Mass Spectrom. Rev. 24, 1–29 (2005)
- Li, G., Li, D., Cheng, Y., Pei, X., Zhang, H., Wang, Y., Sun, J., Dong, M.: Development of a low power miniature linear ion trap mass spectrometer with extended mass range. Rev Sci Instrum. 88, 123108 (2017)
- Huang, Y., Li, G.-Z., Guan, S., Marshall, A.G.: A combined linear ion trap for mass spectrometry. J. Am. Soc. Mass Spectrom. 8, 962–969 (1997)
- Tian, Y., Higgs, J., Li, A., Barney, B., Austin, D.E.: How far can ion trap miniaturization go? Parameter scaling and space-charge limits for very small cylindrical ion traps. J. Mass Spectrom. 49, 233–240 (2014)
- Xue, B., Sun, L., Huang, Z., Gao, W., Fan, R., Cheng, P., Ding, L., Ma, L., Zhou, Z.: A hand-portable digital linear ion trap mass spectrometer. Analyst. 141, 5535–5542 (2016)
- Ouyang, Z., Noll, R.J., Cooks, R.G.: Handheld miniature ion trap mass spectrometers. Anal. Chem. 81, 2421–2425 (2009)
- Contreras, J.A., Murray, J.A., Tolley, S.E., Oliphant, J.L., Tolley, H.D., Lammert, S.A., Lee, E.D., Later, D.W., Lee, M.L.: Hand-portable gas chromatograph-toroidal ion trap mass spectrometer (GC-TMS) for detection of hazardous compounds. J. Am. Soc. Mass Spectrom. 19, 1425– 1434 (2008)
- Ulaby, F. T.; Ravaioli, U. *Fundamentals of Applied* Electromagnetics, 7 ed.; Pearson Education Inc.: New Jersey, 2015
- Dehmelt, H. G. In Adv At Mol Phys, Bates, D. R.; Estermann, I., Eds.; Academic Press, 1968, pp 53–72
- Pau, S., Pai, C.S., Low, Y.L., Moxom, J., Reilly, P.T.A., Whitten, W.B., Ramsey, J.M.: Microfabricated quadrupole ion trap for mass spectrometer applications. Phys. Rev. Lett. 96, (2006)
- Blakeman, K.H., Wolfe, D.W., Cavanaugh, C.A., Ramsey, J.M.: High pressure mass spectrometry: the generation of mass spectra at operating pressures exceeding 1 Torr in a microscale cylindrical ion trap. Anal. Chem. 88, 5378–5384 (2016)
- Moxom, J., Reilly, P.T., Whitten, W.B., Ramsey, J.M.: Double resonance ejection in a micro ion trap mass spectrometer. Rapid Commun. Mass Spectrom. 16, 755–760 (2002)
- Song, Q., Xu, W., Smith, S.A., Gao, L., Chappell, W.J., Cooks, R.G., Ouyang, Z.: Ion trap mass analysis at high pressure: an experimental characterization. J. Mass Spectrom. 45, 26–34 (2010)
- Yang, M., Kim, T.Y., Hwang, H.C., Yi, S.K., Kim, D.H.: Development of a palm portable mass spectrometer. J. Am. Soc. Mass Spectrom. 19, 1442–1448 (2008)

- Xu, W., Song, Q., Smith, S.A., Chappell, W.J., Ouyang, Z.: Ion trap mass analysis at high pressure: a theoretical view. J. Am. Soc. Mass Spectrom. 20, 2144–2153 (2009)
- Schwartz, J.C., Senko, M.W., Syka, J.E.P.: A two-dimensional quadrupole ion trap mass spectrometer. J. Am. Soc. Mass Spectrom. 13, 659–669 (2002)
- Syka, J.E.P., Marto, J.A., Bai, D.L., Homing, S., Senko, M.W., Schwartz, J.C., Ueberheide, B., Garcia, B., Busby, S., Muratore, T., Shabanowitz, J., Hunt, D.F.: Novel linear quadrupole ion trap/FT mass spectrometer: performance characterization and use in the comparative analysis of histone H3 post-translational modifications. J. Proteome Res. 3, 621–626 (2004)
- Sudakov, M.Y., Apatskaya, M.V., Vitukhin, V.V., Trubitsyn, A.A.: A new linear ion trap with simple electrodes. J. Anal. Chem. 67, 1057–1065 (2012)
- Wang, M., Quist, H.E., Hansen, B.J., Peng, Y., Zhang, Z., Hawkins, A.R., Rockwood, A.L., Austin, D.E., Lee, M.L.: Performance of a halo ion trap mass analyzer with exit slits for axial ejection. J. Am. Soc. Mass Spectrom. 22, 369–378 (2011)
- Peng, Y., Hansen, B.J., Quist, H., Zhang, Z., Wang, M., Hawkins, A.R., Austin, D.E.: Coaxial ion trap mass spectrometer: concentric toroidal and quadrupolar trapping regions. Anal. Chem. 83, 5578–5584 (2011)

- Zhang, Z., Peng, Y., Hansen, B.J., Miller, I.W., Wang, M., Lee, M.L., Hawkins, A.R., Austin, D.E.: Paul trap mass analyzer consisting of opposing microfabricated electrode plates. Anal. Chem. 81, 5241–5248 (2009)
- Tian, Y., Decker, T.K., McClellan, J.S., Bennett, L., Li, A., De la Cruz, A., Andrews, D., Lammert, S.A., Hawkins, A.R., Austin, D.E.: Improved miniaturized linear ion trap mass spectrometer using lithographically patterned plates and tapered ejection slit. J. Am. Soc. Mass Spectrom. 29, 213–222 (2018)
- Decker, T.K., Tian, Y., McClellan, J.S., Bennett, L., Lammert, S.A., Austin, D.E., Hawkins, A.R.: Optimal fabrication methods for miniature coplanar ion traps. Rapid Commun. Mass Spectrom. 32, 289–294 (2018)
- Hansen, B.J., Niemi, R.J., Hawkins, A.R., Lammert, S.A., Austin, D.E., Lithographically Patterned, A.: Discrete planar electrode linear ion trap mass spectrometer. J. Microelectromech. Syst. 22, 876–883 (2013)
- Decker, T.K., Zheng, Y., McClellan, J.S., Ruben, A.J., Lammert, S.A., Austin, D.E., Hawkins, A.R.: Double resonance ejection using novel RF phase tracking circuitry in a miniaturized planar linear ion trap mass spectrometer. Rapid Commun. Mass Spectrom. (2018)
- Todd, J.F.J., Mylchreest, I.C., Berry, A.J., Games, D.E., Smith, R.D., Chapman, J.R.: Supercritical fluid chromatography/mass spectrometry with an ion trap detector. Rapid Commun. Mass Spectrom. 2, 55–58 (1988)
- Whitten, W.B., Reilly, P.T., Ramsey, J.M.: High-pressure ion trap mass spectrometry. Rapid Commun. Mass Spectrom. 18, 1749–1752 (2004)