First Principles Optimization of Mass Producible Microscaled Linear Quadrupoles for Operation in Higher Stability Regions

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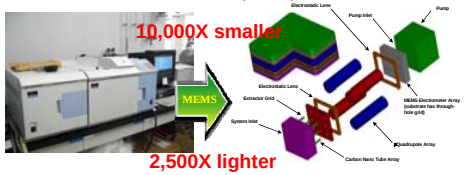
DARPA MTO MEMS

Motivation

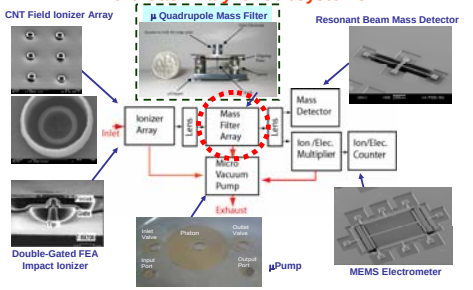
Scaling Down Devices through MEMS Fabrication

- Reduction in size and weight enabling portability (kilograms → grams, m^3 → cm^3)
- Reduction in total system power needed (Watts → milliWatts)
- Potential for integration of semiconductor electronics
- Increasing returns to scale for mass markets

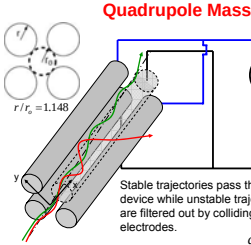
Micro Gas Analyzer Project



Micro Gas Analyzer Subsystems



Quadrupole Mass Filter Physics



Stable trajectories pass through the device while unstable trajectories are filtered out by colliding into the electrodes.

We obtain the Mathieu equation from non-dimensionalizing the equations of motion for an ion within the quadrupole field.

Quadrupole Potential

$$\Phi(x,y,z,t) = \Phi_0(t)\cdot\frac{(x^2-y^2)}{2r_0^2}$$

$$\Phi_0(t) = U - V\cos(\omega t)$$

Mathieu Parameters

$$a_x = -a_y = \frac{8qU}{mr_0^2\omega^2}$$

$$q_x = -q_y = \frac{4qV}{mr_0^2\omega^2}$$

Mathieu Equation

$$\frac{d^2u_{x,y}}{d\xi^2} + [a_{x,y} - 2q_{x,y}\cos(2\xi)]u_{x,y} = 0$$

where $u_x = \frac{x}{r_0}$, $u_y = \frac{y}{r_0}$; $\xi = \frac{\omega t}{2}$

Higher-Order Harmonics and Non-linear Resonances

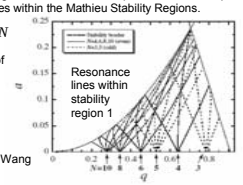
$$\Phi = \Phi_0[\cos(2\theta)(\frac{r}{r_0})^2 + \frac{C_4}{C_2}\sin(4\theta)(\frac{r}{r_0})^4 + \frac{C_6}{C_2}\cos(6\theta)(\frac{r}{r_0})^6 + ..]$$

Ideal quadrupole term — Higher-Order, non-ideal terms

Geometric non-idealities contribute to higher-order terms in the potential. This couples the x-y motion, and generates instabilities within the Mathieu Stability Regions.

$$n_x\beta_x + n_y\beta_y = 2\nu \; ; \; |n_x| + |n_y| = N$$

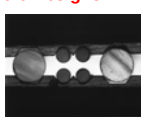
- β_x, β_y are the fundamental periods of motion in x and y
- n_x, n_y, and ν are integers
- N = k, k-2, k-4, … 4 or 3
- k is the highest order term



Equations were derived rigorously by Y. Wang and J. Franzen.

Microfabricated Planar Quadrupole Designs

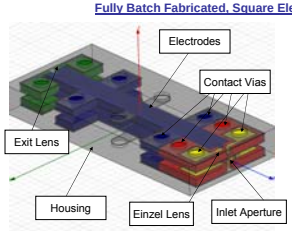
M.G. Geear, R.R.A. Syms, S. Wright, A.S. Holmes; JMEMS, 2005



S. Taylor, R.F. Tindall, R.R.A. Syms; J. Vac. Sci. Tech. B, 2001

Pros: conventional round electrode geometry minimizes higher-order effects
Cons: requires manual insertion/assembly of electrodes after device fabrication

Fully Batch Fabricated, Square Electrode Design



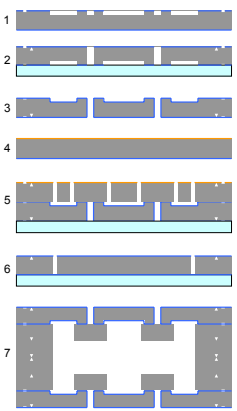
Concept

- Remove manual assembly to enable mass production
- A fully batch fabricated MEMS quadrupole mass filter
- Rectangular electrodes required due to fabrication constraints and capabilities

Questions

- Square electrodes will reduce the performance but is there a way to compensate for or minimize this reduction?
- How will using silicon instead of metal affect the physics?

Proposed Device Process Flow



1 - Etch shallow release pits in cap wafer.

2 - Etch through-hole vias on backside of wafer from step 1.

3 - Strip oxide and grow insulating oxide on wafer from step 2.

4 - Create wafer with one side nitride and one side oxide.

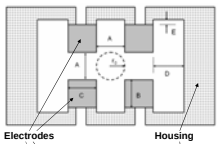
5 - Bond wafer from step 4 on wafer from step 3. Pattern electrodes.

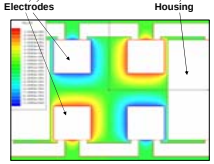
6 - Pattern spacer wafer with DRIE.

7 - Strip nitride from two stacks made in step 5. Strip oxide from one wafer made in step 6. Bond pieces together for complete device.

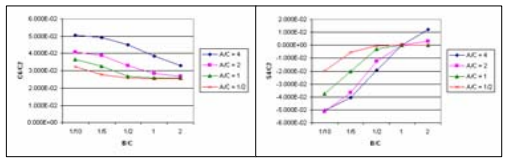
Silicon — Nitride — Oxide — Quartz

Device Parameterization and Optimization

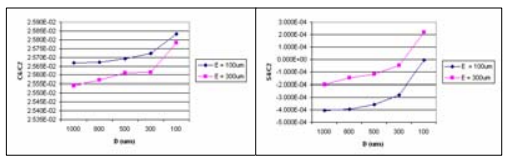




Crucial device dimension were parameterized. Potential field solutions were solved in Maxwell 3D. Solutions were exported into a MATLAB script to perform multi-pole decomposition. We would like to minimize the higher-order terms.



Significant terms of the multi-pole expansions without housing. C_2 is the ideal quadrupole term.



Significant terms of the multi-pole expansions with housing and dimensions A = B = C = 1000um.

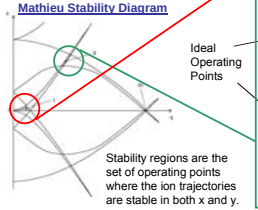
Operation in the Second Stability Region

μ-Gripper Quadrupole Performance

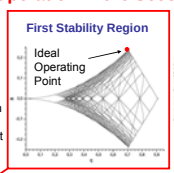
Experimental data using the μ-Gripper quadrupole (L.F. Velásquez-García, MIT) shows improved peak shape and resolution when operated in the second stability region.

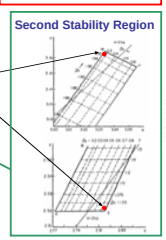
The effects of device imperfections are much more apparent when operated in the first stability region since the ideal operating point is at the apex of the region, where many non-linear resonances converge.

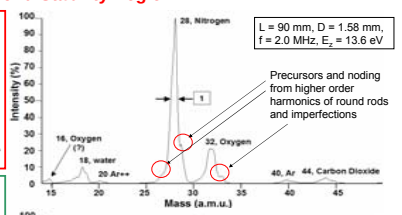
Mathieu Stability Diagram

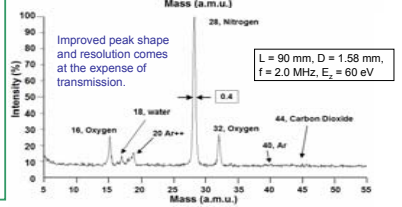


Stability regions are the set of operating points where the ion trajectories are stable in both x and y.









Results

The minimum dimension of the electrode should be larger than the dimension of the aperture to minimize the higher-order coefficients (**B** or **C** should be larger than **A**).

The distance from the electrodes to housing walls should be equal to minimize the odd coefficients (**D** should equal **E**).

Having a larger top gap (dimension **E**) will reduce the C_6 coefficient slightly while increasing the other coefficients substantially. It is optimal to have a smaller **E**.

Simulations show that doped silicon (5mΩ-cm) driven at 4 MHz behaves as a pure metal, clearing concerns on material performance.

It is believed that operation in the second stability region will provide a means to overcome the non-linear resonances introduced by the square electrode geometry.

Presenter Information

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