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Compact Ion Traps Set Ups for Quantum Networking and Quantum Information Processing

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Abstract

This work is in the context of realizing a practical large scale quantum information processing (QIP) platform. Interest in finding such a platform increased rapidly soon after quantum algorithms were shown to exhibit computational power believed to be intractable by classical computers. Atomic ions in Paul traps were among the first experimental systems proposed as a realistic QIP platform. When composed of few ions, these systems have demonstrated fidelity meeting the quality threshold set by current fault tolerance algorithms.
Many current trapped ion quantum information processing experiments are unwieldy, occupying a large research laboratory. This makes the experiments more susceptible to noise sources that can easily be eradicated with compact ultrahigh vacuum chambers, compact laser setups, and ion traps tailored to the specific experimental needs. As the field progresses, these compact systems will become increasingly more important. The goals of this work are to design a 3D microfabricated trap that supports equally spaced equilibrium ions positions and the construction of a compact vacuum system. Which in the next stage will allow as to operate the traps in a compact experimental set up and provide a quantitative analysis of the benefits and drawbacks such compact systems.

Introduction

The realization of universal quantum registers promises to outperform their classical counterparts for purposes of sensing, communication, networking, computation, and more. Due to their long lifetimes and the exquisite control possible over both the internal and external degrees of freedom, trapped ions are one of the most promising platforms for the realization of such a quantum device. However, most current implementations use bulk setups that occupy nearly an entire room. As quantum technologies progress in capability, these large setups will quickly become inadequate for many applications, including those where size and weight could be limiting factors.

The trapped-ion group at the Weizmann Institute of Science, led by Prof. Roee Ozeri, is working towards realizing trapped-ion registers of up to a few tens of Sr^+ qubits, for realizing quantum error-correction codes, quantum simulations, and metrology. Reaching these goals requires to develop and improve on local control of ion-qubits, implement high fidelity entanglement operations on pairs of ions in a linear chain, and improve on the initialization and detection fidelities. Most current trapped ion experiments are made from bulk components and occupy a large research laboratory. This leads to excessive noise and decoherence of differing origins, such as laser beam fluctuations and drifts. This is partially due to the long distances between the laser source and the final ultrahigh vacuum (UHV) chamber where the ions reside. In addition, most UHV chambers tend to be bulky and so require a lot of time to assemble and occupy a significant fraction of an optical table. Making these UHV and laser setups more compact would lead to more robust operation and drastically reduce the upkeep time currently required by many experiments. Finally, tailored ion trap designs are required to fit the experimental tasks, otherwise, the traps are either insufficient or too elaborate for the specific experimental needs. This can lead to modifications or extraneous connections that can often result in unnecessary experimental complications. Here we aim to develop a compact physical system including microfabricated trap, vacuum system and laser system that will advance the capabilities and performance of trapped ion experiments in the field of quantum information.

Our research during this year consisted of two parallel tasks. The first task aims to developing a micro-fabricated trap that will meet our specific needs. This compact trap will be tailored to trap linear crystals to accommodate the experiments discussed above this include trap simulation, modeling, and understanding the fabrication capabilities.

In parallel, we have designed and constructed a compact vacuum system as well as the complete lasers system that is required to run the experiments and quantify the system performance. Since in this stage, we still don't not have the micro-trap at our disposal, we carried out the measurements using a macroscopic segmented blade ion trap. We have evaluate the base pressure that can be reached in our compact system where the ion itself was used as the vacuum gauge by monitoring collisions with the background gas. This is because UHV gauges that can reach 10^-11 Torr are bulky and cannot be used in a compact system. Moreover, this type of gauges (Bayard Alpert) uses filaments that cause significant outgassing and became the dominant source in the case of compact system that have low pumping speed.

Trap design and simulation

The subject of this task is to design an ion trap capable of trapping tens of ions in a uniformly spaced linear chain. Due to the stringent requirements on electrodes shape and alignment for the generation of required trapping potentials, we designed the trap to be compatible with a precise micro-fabrication process that is relatively simple and does not require special fab capabilities.

The trap is assembled out of five silica glass wafers, stacked one over the other. The middle wafer, called the spacer wafer, defines the ion-to electrode distance along one direction (which we call 'y'). Above and below it there are two wafers called the electrode wafers, designed to generate the appropriate DC and RF potential for the ion chain. Above the upper electrode wafer and below the bottom electrode wafer are the two compensation wafers, hosting DC electrodes for cancellation of stray electric fields. Each wafer is designed to accommodate other requirements and features, making them different in geometry from one another. Images of the five wafers and the entire assembly are presented in figure 1(a). The four upper wafers horizontal sizes are constraint by a 1.5 cm x 1.5 cm square, while the bottom wafer is larger by about 3mm in each direction, to accommodate holes for later fixing the wafer stack to a chip carrier or filter board. The height of the trap when assembled is 2.17mm.
The purpose of the two electrode wafers is to generate the required complex trapping potential. The wafers defines both the RF and DC electrodes, which are assembled in a two-layer symmetric configuration described in figure 1(b). Each horizontal pair of RF and DC electrodes are defined on either one of the two electrode wafers. Being so, the horizontal distance between RF and DC electrode lines are defined by each wafer geometry, and the vertical distance is defined by the assembly of one wafer with respect to the other, with the aid of the spacer wafer.

(a) (b)

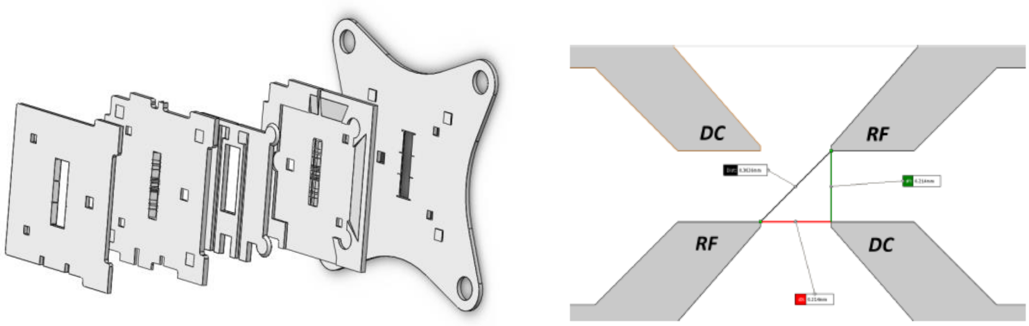


Figure 1. (a) Exploded view for the five wafer stack. (b) Side cut of RF and DC elec trodes

The vertical and horizontal electrode distances where chosen such that the distance from an ion to the nearest electrode surface would be 150 μm. While closer electrodes induces larger gradients and deeper trapping potentials, the minimal ion electrode distance d is practically limited by electrode induced anomalous heating of the ions. The field fluctuations heating the ions where shown to scale as $1/d^4$, giving rise to high motional decoherence rates for very small traps. Together with the desire to have non-diverging axial laser beam, we chose the aforementioned ion to electrode distance. The width-height aspect ratio is one, contributing to deeper traps and establishing a view angle of 82.5^o corresponding to a NA= 0.66.
As discussed, the middle wafer determines the two electrode wafers distance and relative alignment. It does so by precisely define three support points of contact for each of the two

electrode wafers, which together with the design of contact points in the electrode wafers results in the accurate alignment of both wafers with respect to one another. The middle wafer thickness is 500 μm. This is enough to constitute a 214 μm distance between the two wafers, but also to allow for the integration of two more features: axial optical access window and RF current carrying wire. The ions will be suspended in the middle of the spacer wafer, where there is a large rectangular hole. The width of the hole, 2 mm, was chosen to ensure large distance from the ion to the closest dialectic surface. Its length, 6 mm, was determined to contain the central complex experimental zone, along with two trapping regions to trap ions coming out of the oven.

The compensation wafers are the bottom most and upper most wafers in the trap assembly. They each host six compensation electrodes, each of which should generate a nearly homogeneous gradient over the chain length. The bottom electrode wafer has 2mm diameter wide holes in each of its corners to be used for mounting the trap to an electronic filter board, serves to physically connect and filter DC and RF signals fed to the trap. The wafers also have four rectangular legs as for aligning and gluing these wafers to the electrode wafers, and three holes each to increase the vacuum conductivity of the gap between the two wafers when mounted.

To take advantage of the trap precise micro-fabrication and the fact that there are no end-cap electrodes in the trap, we have drilled a squared window tunnel through the spaced wafer. Coinciding with the axial axis, this window provide optical access for laser beam parallel to the chain direction. Such optical port can be used for multiple purposes: as a global beam for axial addressing, a global Raman beam, cooling/imaging beam or alternatively use a laser to generate a periodic intensity pattern as a tool in quantum simulations. To keep the middle wafer intact, we left about 85 μm above and below the window. The new window size of 330 μm set a constraint on the beam waist size at the window plane, and consequently constraint the focused spot size of the beam through the Gaussian beam relation The expression for the radial field of a truncated Gaussian beam is complex, but numerical estimation of the intensity in the side-lobes indicates that a truncation ratio $T = 2w_0/L$ of less than 0.5 results in negligible intensity leak outside the main lobe. The minimal spot size is wavelength dependent, but to have low scattering of the electrodes, the beam waist w_0 should be considerably smaller than 150 μm, the ion-to-electrode distance.

All five wafer host electrical wires to provide the electrical potential at the designated electrodes. The electric wires are defined by evaporating gold on the wafer's faces, with appropriate evaporation masks are used to determine the wiring pattern on each wafer. The electric wires from each wafer are to be wire bonded to the filter board, onto which the trap will be mounted. The electrode pads, which are the surfaces into which connecting wires will be bonded, are all placed along the border of a 1.5 cm square bounding the four upper most wafers. All electrodes are approachable from above the trap, and each wafer's boundary was designed to provide access to electrodes from wafers below it. Figure 2(a) present a view of the trap from above with all electrodes sketched. The encompassing square is colored to highlight the wafers to which each pad belongs to (and also indicate the different height levels each pad is at). The two compensation wafers contain six DC electrodes each, which are placed near the four corners of the square. The two compensation wafers hosts 17 DC electrode plus one RF electrode each. In each wafer, the DC side is densely routed, with inter wire spacing reaching tens of microns where they are closest. Capacitive coupling between these electrodes is not an issue, as they are to be operated at DC. The RF electrode is a single

(a) (b)

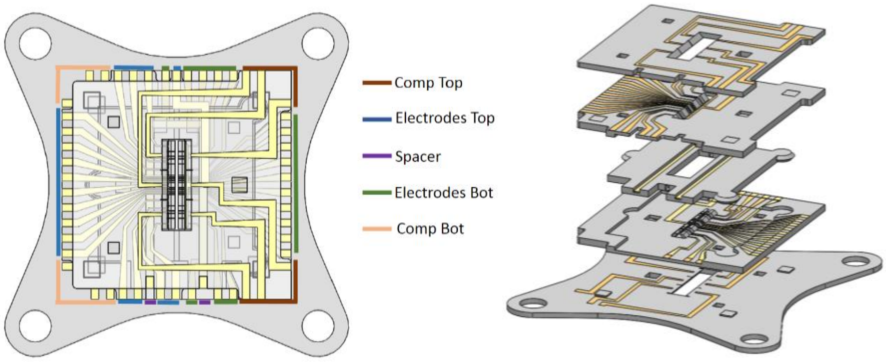


Figure 2 : Electrodes wiring. (a) Top view, detailing electrode pads structure. (b) Wires routing is done on the upper facing side of each wafer.

wire on each wafer, providing the same RF potential to the entire electrode line. Figure 2(b) presents the wires routes on each wafer.

The design towards generation of complex trapping potentials is manifested in the structure and size of the electrodes in the electrode wafer. The linear trapping region is practically divided into three zones, as presented in figure 3(a). The middle region, highlighted with green, is the experimental zone designated for the trapping of long equidistant ion chains. The trap axial potential is defined using nine DC electrodes, composed of a larger middle electrode of size 300 µm and four pairs of 100 µm electrodes. This configuration was chosen after an extensive search over many possible electrode sizes using COMSOL FEM simulations. Figure 3(b) show simulation result of optimal electrodes voltages to generate the potential for equidistance 50 ions chain. The two other zones highlighted in red are the loading zones, and are similar to one another. Ovens emitting Sr or Ca atoms would be directed to the middle of these regions, and after being ionized they should be trapped there. Trapping ions emitted from the oven does not require complex axial potential profile, hence the electrodes are generally larger. However, the middle smaller electrode in the trapping region was designed for the purpose of splitting a chain of trapped ions, potentially loading part of the trapped ions into the experimental region.

(a) (b)

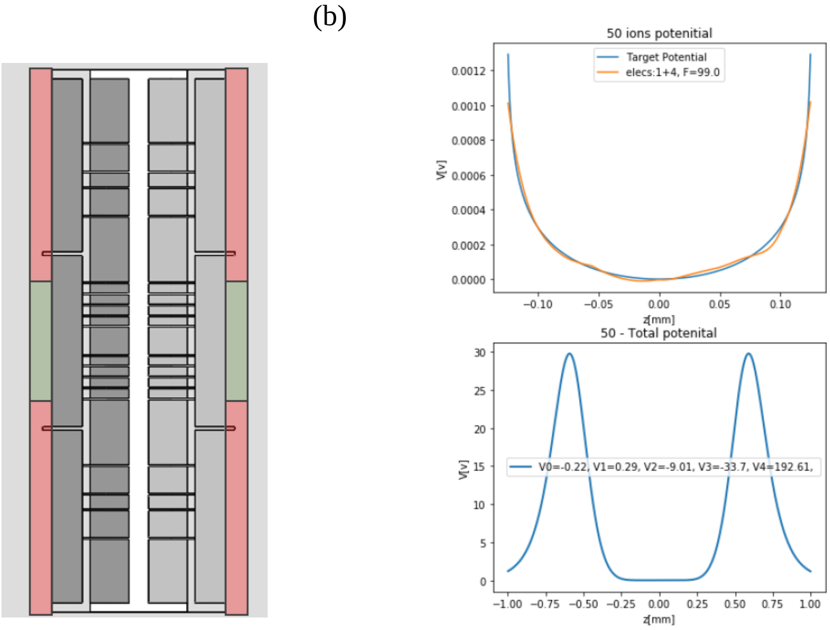
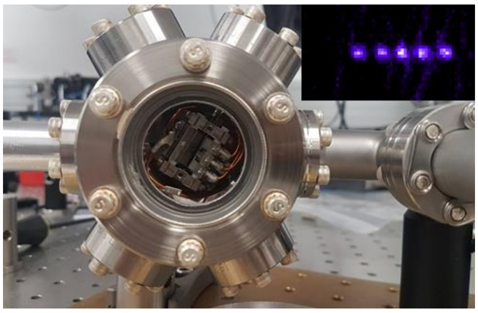


Figure 3: (a) Trapping electrodes as viewed from above. (b) Axial trapping potential for 50 equidistant ions

Compact vacuum system

In parallel to the design of the microfabricated trap we constructed a compact vacuum system that consists of a small size 2 L/s ion pump and small NEG element that should add another 5 L/s of pumping speed mostly for H_2. The total weight of the vacuum system was less than 3 kg. Since the new trap was not fabricated yet, to test the system we used a bulky hand-assembled ion trap. The trap and the compact vacuum chamber is shown in figure 4(a). Due to the small size of the system we did not have a vacuum gauge to measure the pressure but rather used the ions themselves as the pressure sensor. We evaluate the pressure by trapping two Sr^+ ions of different isotopes 88 and 86. Since our lasers were on resonance only with the 88 isotope the 86 ion was always “dark”. Next we monitored the position of the 88 ion in the two ion crystal using an EMCCD camera for few hours and record every time its position was change. These events are due to collisions with background gas and therefore allow us to estimate the pressure in the chamber. Figure 4(b) presets the result of such measurement, from the distribution of time between collisions we estimate an average collision rate to 0.025 1/sec which correspond to pressure of 1-2 $x10^{-10}$ Torr. This result is almost an order of magnitude higher than what we expected and after further testing we found out that one of the windows had a leak. These days we are working on fixing this problem and believe that the result we are aiming for will be achieved soon.

(a)



(b)

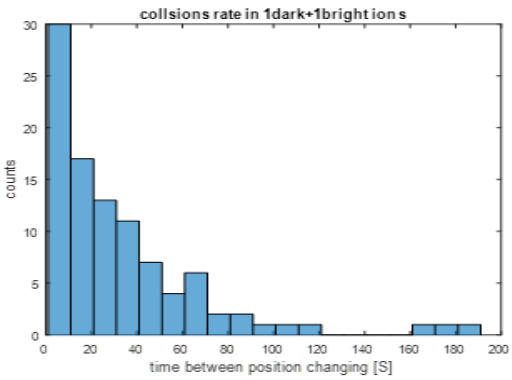


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Figure 4. Compact vacuum system. (a) Picture of the vacuum system with a bulky blade-trap. The upper right side is a picture of five Sr+ ion-crystal. (b) Histogram of time between collisions measurement with an average collision rate of ~0.025 1/s.

Summary

In this work we design a 3D segmented ion trap which can be microfabricated based on fused silica wafer stack. We tested different geometries and by simulating the electric trapping potential, we found a geometry that satisfy all the requirements and in particular allows to trap up to 50 ions in equidistant configuration. In addition we constructed and compact setup including lasers and vacuum system. These days we are in a process of fabricating the trap we designed and hope to be able to test it in the compact system in the near future. This work is the first stage in realizing compact system for quantum information processing and quantum networking with trapped ion.

Significant Collaborations that resulted from AOARD supported project:

As part of this research work we initiate a collaboration with the AFRL trapped-ion group in Rome, New York, led by Dr. Soderberg and Dr. Tabakov. The AFRL group is working towards quantum networking and distributed quantum computing using trapped ions as memory nodes. The challenges in those field of research largely overlap the goals of the work that is described here. A side of sharing with the AFRL group our results and know-how that came from this work, we also hope to be able to deliver one of our traps to be tested in their labs once these will be available.