Monolithic 3D-Printed Ions Trap

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***Abstract*—This study explores the fabrication process of 3D-printed ion traps for trapped ion quantum platforms and their advantages. By leveraging 3D printing and angled thermal metal deposition, a novel monolithic ion trap design is proposed to achieve enhanced performance in ion confinement, scalability, and operational stability. The integration of advanced manufacturing techniques enables the creation of deeper potential wells and higher trap frequencies while addressing challenges like surface roughness through precision coating techniques. The fabrication process incorporates two-photon polymerization for detailed geometries and thermal evaporation for selective metallization. The proposed design meets the DiVincenzo criteria for quantum computing, providing a scalable and efficient platform for future quantum devices. Future work will explore the integration of photonics and vertical trap arrays to advance further the scalability and functionality of ion trap quantum systems.**

***Index Terms*—ion trap, quantum computing, 3D printing, angled thermal evaporation**

I. Introduction

Ions trapped in radiofrequency (RF) traps can be used for many different quantum technologies, such as atomic clocks, quantum sensors, and quantum information processors (QIP). They enable fast and high-fidelity state preparation and measurement (SPAM), along with single- and two-qubit operations using either optical or electronic gates, which are important for all quantum technologies.

The traditional Paul traps for these experiments use oscillating electric fields to confine charged ions in three dimensions. They are essential for isolating and manipulating individual ions, which serve as qubits. Surface traps are a shrinkable variation where electrodes are patterned onto a flat substrate. While surface traps advance scalability by integrating complex electrode patterns onto flat substrates, they also introduce notable challenges. A primary shortcoming is the increased electric field noise due to the proximity of ions to the electrode surfaces, which can cause decoherence and unwanted heating of the qubits [1]. A Paul Trap uses 3D printing and angled thermal metal deposition to create a novel trapping structure that can confine ions using a near-perfect quadrupole electric field, expanded design freedom, and improved cooling requirements. With 3D-printed Paul traps, the desired quadrupole potential can be reached with 2 RF resistors and guaranteed larger trap depths, higher trap frequencies, and scalability.

II. Background

The rapid oscillations at Ω_{RF} frequency of the electric field create a time-average, or "pseudo", potential, $\psi(\mathbf{r})$, proportional to the square of this field's amplitude, $|E(\mathbf{r})|$. For a particle with charge e and mass m in an oscillating electric field, the time-invariant pseudopotential is:

$$\psi(\mathbf{r}) = \frac{e}{4m\Omega_{\text{RF}}^2}|\nabla\Phi_{\text{RF}}(\mathbf{r})|^2 = \frac{e}{4m\Omega_{\text{RF}}^2}|E(\mathbf{r})|^2 \tag{1}$$

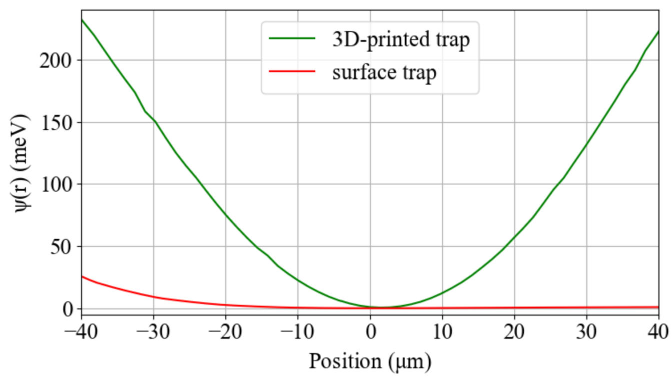

Fig. 1: **Simulation done by Team: Pseudopotential on the radial axis with origin at the rf-null point**

This approximation is useful for treating the trapping potential as a standard time-independent potential well. From COMSOL Multiphysics, the team extracted the electric field that gives the pseudopotential approximation following Equation 1, Figure 1 shows the pseudopotential approximation for surface and 3D-printed traps. The ion is trapped at the rf-null point, the position where the pseudopotential is essentially zero. This rf-null point is the minima at position 0 seen from Figure 1. The figure also demonstrated the larger trap depth for the 3D-printed trap $\geq$ 200 meV. The higher curvature also gives a more perfect harmonic oscillator where trap frequencies are highly dependent.

III. Design Proposal

A. 3D Printing

The use of 3D printing for ion traps is relatively new and comes with many advantages. The first being the ability to construct more complicated geometries to improve ion confinement and stability. This new manufacturing method can help create geometries that are able to have deeper potential wells, and have higher radio frequencies, reducing error rates in its operations. This can also be manufactured quickly, which helps the scaling for quantum systems. This enables rapid prototyping and allows iterative improvements to the trap geometry quicker. One challenge in this new manufacturing process is the surface roughness post-printing, which is mitigated by applying surface coatings [2]. Another challenge is the geometry preventing/obstructing the laser from accessing the wells for manipulating and cooling ions.

B. Angled Thermal Deposition

Angled thermal evaporation in addition to 3D printing would leverage the geometric flexibility of 3D printing with the precise surface engineering and material capabilities of thin film deposition. Following the fabrication of a 3D-printed structure, the component is placed in a vacuum chamber to undergo angled thermal evaporation. This process involves the directional deposition of vaporized conductive material, controlled by carefully adjusting the angle of incidence of the vapor stream. This ensures that only the exposed surfaces are coated, enabling the precise metallization of electrode regions while preserving the insulating characteristics of unexposed areas. This method is directly inspired by its demonstrated effectiveness in the fabrication of monolithic microtrap arrays, wherein gold and titanium were deposited onto the internal surfaces of silica apertures to form conductive electrodes while maintaining insulating gaps to mitigate the risk of electrical breakdown [3]. Such precise deposition is critical for ensuring the electrical and thermal properties required for stable ion trapping operations.

This integration of angled thermal evaporation and additive manufacturing offers significant potential for creating scalable and efficient ion traps. By limiting metallization to critical electrode areas, this method preserves the mechanical and thermal stability of the underlying 3D-printed base structure. Additionally, the approach enables the development of intricate electrode geometries and insulating regions essential for stable trapping potentials [3].

C. Trap Design

The goal of this design is to reach the desired quadrupole potential with 2 RF resistors while still ensuring larger trap depths, higher trap frequencies, and scalability. The DiVincenzo Criteria is a list of requirements to build a quantum computer; the design considerations for this trap are based upon these principles. The design for this device will be a 3D monolithic trap where the trap electrodes are formed of a gold-coated silica [3]. By using gold and silica, a unit-aspect ratio trap can be achieved which enables an efficient trapping potential. Additionally, the low-resistivity Silicon reduces radiofrequency losses which allows for low temperature dissipation. Inside the trap aperture, there is an exposed SiO2 insulating gap of 50 um (between the gold electrodes and the bulk silicon) to prevent electrical breakdown. As seen in the diagram, the gold electrodes cover the silica surface which helps to reduce the amount of insulator (for electrical isolation) that is visible to the ion. This design is represented by Figure 2 and Figure 3.

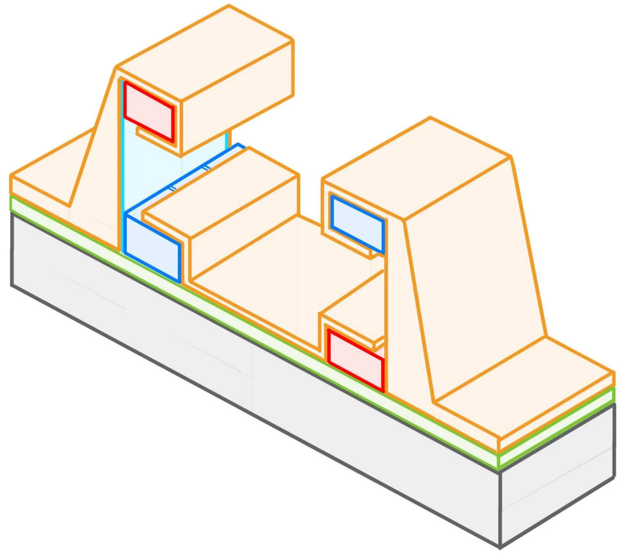

Fig. 2: **Isometric view of trap**

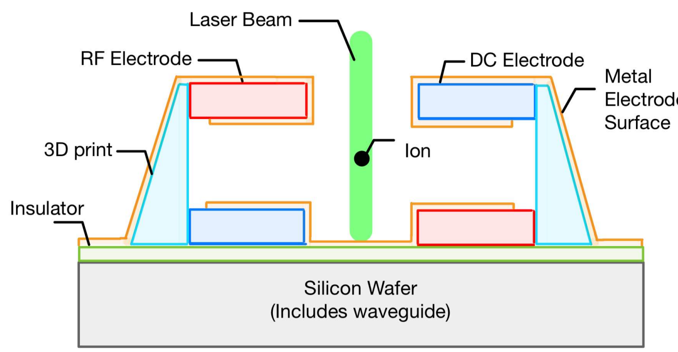

Fig. 3: **Cross-section view of trap**

IV. Fabrication

A. Challenges and Techniques

Fabrication of ion traps with complex 3D architectures requires innovative solutions to overcome limitations in conventional manufacturing techniques. Standard photolithography, a staple for flat-surface patterning, is less effective when dealing with intricate geometries is less effective when dealing with intricate geometries, limiting its use for 3D electrode structures. Advancements in additive manufacturing, specifically two-photon polymerization provide an opportunity to achieve sub-micron resolution in creating these detailed geometries [2].

3D printing allows for rapid prototyping with lower costs to produce samples. Designs can be created, fabricated and then tested within a 1-2 day time period. Standard micro-fabrication techniques like photolithography and focused ion beam milling require expensive clean-rooms and special equipment. The 3D printing used would use less expensive tools and systems, making even smaller researchers to do their own tests at a much lower cost. Reproducibility is a likely challenge that will be faced, such as a variety in printer resolution. Though this can be mitigated by following high-precision calibration and using standardized printing parameters.

The use of gold as the conductive material provides excellent electrical conductivity and resistance to oxidation, ensuring the long-term stability and reliability of the fabricated ion traps. Integrating conductive materials onto these structures presents a significant challenge. To address this, the team employs angled thermal evaporation to selectively deposit conductive layers of gold onto the desired electrode surfaces. This technique ensures precise metallization of the electrodes while preserving the insulation of non-exposed regions [3].

B. Process and Methodology

The following sections outline the step-by-step process utilized in the fabrication of the 3D ion trap structure, accompanied by figures for clarity. This process integrates material selection, additive manufacturing techniques, and precise metallization to achieve the desired architecture.

Step 1: Material Preparation: As seen in Figure 4, for ion micro trap fabrication, an oxidized silicon wafer will be used. The wafer will be n-doped with arsenic or phosphorus and will have an approximate thickness of 300 um. Silicon dioxide (SiO2) thin film will be deposited onto the substrate via thermal oxidation. This silica layer will act as an electrical insulator and allow for the addition of the electrode structures.

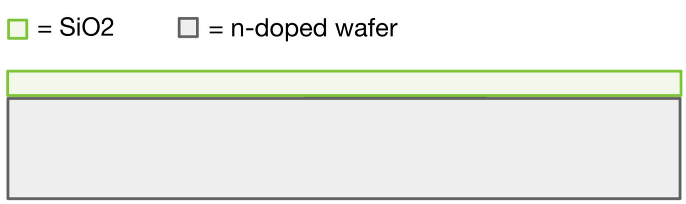

Fig. 4: **Silicon dioxide film**

Step 2: Optical Lithography: The bottom electrodes will be deposited using optical lithography. First, the photoresist is applied to the wafer through spin coating & a soft bake is used to stabilize the resist film. Second, optical lithography (or Photolithography) using UV light is done to pattern the electrodes. Routing metal lines between Ion traps are also patterned and deposited onto the wafer. These steps can be seen in Figure 5 through 8.

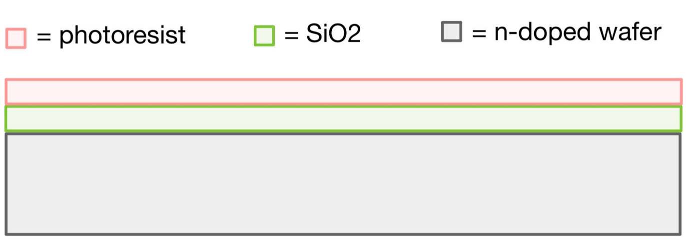

Fig. 5: **Deposit photoresist**

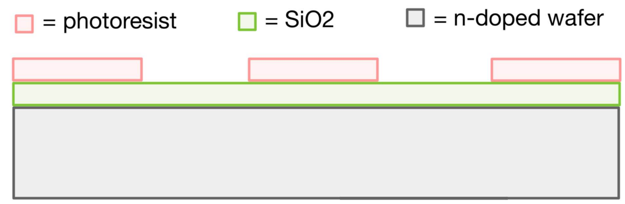

Fig. 6: **Pattern photoresist**

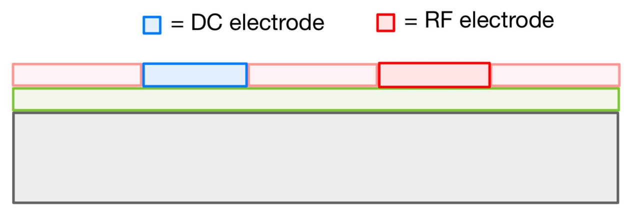

Fig. 7: **Deposit electrodes**

Fig. 8: **Remove photoresist**

Step 3: 3D printing: As seen in Figure 9, the 3D monolithic trap architecture is formed directly on the wafer utilizing a two-photon polymerization printing process. Figure 10 shows the deposition of silica-based resin to form the trap structure and upper electrode structure.

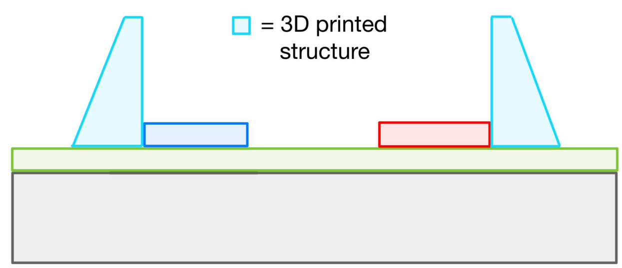

Fig. 9: **3D print trap structure**

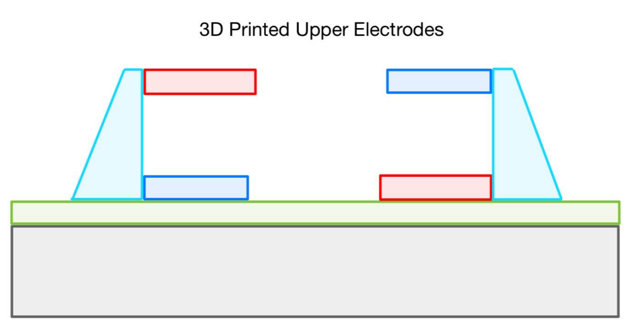

Fig. 10: **3D printed upper electrodes**

Step 4: Angled Thermal Evaporation: Coat the internal surfaces of the 3D printed silica structure with gold to form the final electrode surface of the 3D quadrupole. Mount the wafer into the evaporation chamber with a tilting and rotating stage. Systems such as those from Angstrom Engineering can provide precise metallization. Deposit a thin layer of gold (50 nm) at all relevant electrode surfaces. These steps can be seen in Figure 11.

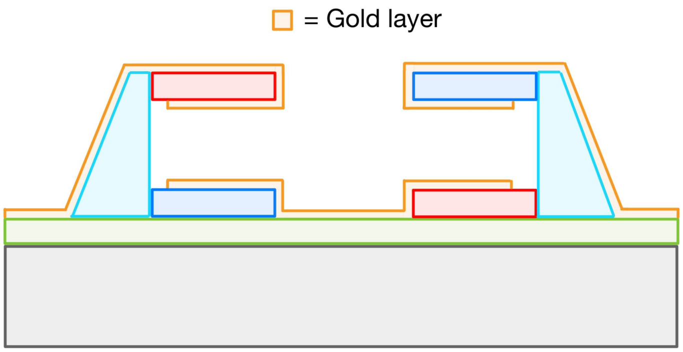

Fig. 11: **Deposit gold layer**

V. Future Work and Conclusions

Quantum computing is a growing field and there are many opportunities for improved reliability and efficiency. For example, the integration of photonics with ion trap arrays can be a huge step towards scaling quantum processing. The goal of integrated photonics is to use complex photonic circuits to transmit light similar to how integrated circuits transmit electronic signals. With the use of waveguides and multimode interferometer (MMI) splitters, optical signals can be delivered to control multiple ions in a surface trap [4]. The waveguides allow for efficient light delivery and the MMI-integrated splitters can divide single optical inputs into multiple output channels; as a result, it would be possible to scale up the number of qubits in the trapped ion processor [4]. An additional design that is under development is 3D Trap arrays. These arrays consist of several distinct regions where the ions can be manipulated. Fabrication of these apertures requires electrical VIAs and can even enable traps to be vertically stacked [3].

In conclusion, research was conducted on a 3D monolithic where trap electrodes are formed of gold-coated silica. The design aimed to achieve the desired quadrupole potential with 2 RF resistors while still ensuring larger trap depths, higher trap frequencies, and scalability. The fabrication involved angled thermal evaporation and 3D printing. The goal was to utilize the geometric flexibility of 3D printing and the precision of thin film deposition to preserve the mechanical and thermal stability of the structure.

VI. Acknowledgment

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