

**Concept analysis and fabrication of an ion trap to
couple negative and positive ions**

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Abstract

The realization of an universal quantum computer remains at the core of quantum information research. Achieving precise control of quantum bits (qubits) will introduce new standards for computation and enhance our global knowledge. Ion trapping is a promising approach to reach this goal since it leads to long coherence time of quantum states. On remaining challenge in this technology is the scalability of the electrodes. Indeed, miniaturising the ion traps to build a quantum processor with large number of qubits, currently leads to higher heating rate as the electrode-ion distance goes down. One potential way to improve the scalability of ion traps could be to use both anion and cation, unlike current experiments that are only performed with positively charged ions. It could allow us to bring the ions closer to each other while keeping a reasonable distance to the trap electrodes. This work gives a description of this innovative approach with the fabrication of a new trap.

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Introduction

The quantum information theory find its origin in a paper of Richard Feynman in 1982 [1]. In this paper, he studies the possibility of simulating physics with a classical computer. He came to the conclusion that a standard computer can give great results through a classical approximation but it cannot simulate quantum systems in a reasonable amount of time. This can be partly explained by the fact that superposition of states for quantum object leads to algorithm with exponential complexity. Following this reflection, Richard Feynman developed the idea of a computer using, as basic unit of computation, a two levels quantum system instead of the standard ‘bit’. The concept is to take advantage of quantum mechanics properties, like superposition and entanglement, to simulate complex systems. This unit of computation is named quantum-bit (qubit). The theory of quantum information continued to be developed these last decades with some great success like quantum teleportation [2] in 1993 and Shor’s algorithm [3] in 1994.

Nowadays, the challenge is to use modern capabilities to develop a functional quantum computer. At this stage, several qubit technologies are in study. One well-known choice is superconducting qubit. In 2019, Google announced quantum supremacy with their 54 superconducting qubits processor [4]. Beside this, a lot of other techniques are in development like photonic computer [5] and trapped ions. A main advantage of ion traps is their stability over time. Indeed, a superconducting qubit has a lifetime in the order of a few hundred of microseconds [6] while trapped ions can keep quantum information close to a minute [7]. However, please notice that superconducting qubits can be operated much faster than trapped ions and, in general, it is not possible to accurately compare the existing technologies since they all are in development. One main issue in ion traps consists in their bad scalability. This work explore a potential way to improve it by using negative ions in quantum systems.

Trapped ion qubits are realized by catching ions in electrostatics potential well. As stated by Earnshaw’s theorem, a static electrical potential cannot confine a charge in all direction of space. This statement is explained in the first section of this thesis. From this consideration, there is two major techniques to achieve ion traps: the Penning traps and the Paul traps. Penning traps are using a strong magnetic field for the radial confinement of the ions where Paul traps are using radio-frequency (RF) electric fields. Once trapped, the quantum information is encoded on the ion internal electronic levels. Therefore, the choice of the ion is crucial for the realisation of a stable two-levels quantum system. The easiest atomic structure to handle is ‘alkali-like’ ions which have, once ionised, only one valence electron on a S orbital. One main advantage of S orbital is that it carries zero angular momentum since it corresponds to a sphere around the nucleus. Some example of suitable candidates for trapped ions qubit are Be^+ , Mg^+ , Ca^+ . Finally, several possibilities are available for the energy levels to encode quantum information. This leads to different type of qubit: Zeeman, Hyperfine or Optical [8].

In all existing trapped ions architectures, only positive ions are used to encode and transport quantum information. This choice can be explained by the fact that positive ions are much more stable and easy to produce than negative ions. However, the use of both positive and negative ions can be a great asset in the perspective of building a quantum computer. Actually, to couple two positive ions via Coulomb interaction, the potential shape is a 4^{th} order polynomial function, whereas only the 3^{rd} order is required when charges of opposite signs are used. Moreover, making higher order potentials needs larger voltages that are limited by ionisation of dielectric materials between the electrodes. One direct consequence is the difficulty to set small distances between two positive ions while conserving a reasonable distance to the trap electrodes. Furthermore, decreasing the electrode-ion distance leads to higher heating rate and therefore smaller qubit lifetime. Hence a limitation in term of system scalability. Making use of negative ions would have as main benefit to have the possibility to bring ions closer to each other with smaller voltages thanks to the 3^{rd} order potential shape. The goal of this project is to analyse the advantages of building a modified quantum charge-coupled device (QCCD) architecture making use of both positive and negative ions and to build a Paul trap to study this innovative approach in a dedicated setup.

In the first chapter, a theoretical study about Paul traps, energy exchange and two-qubits quantum gates in this modified QCCD architecture are investigated. The second chapter of this thesis explain to the reader the benefits of using positive and negative ions in term of voltage and coupling. This is demonstrated by a simulation of planar Paul traps with optimized design in both positive-positive and negative-positive ions cases. In the third chapter, the model of the ion trap made by Ilia Sergachev - engineer in the Trapped Ion Quantum Information (TIQI) group - is described as well as the experimental chamber, accordingly designed to take use of this new trap. Finally, the fourth part of this thesis details the fabrication work done in ETH Zurich cleanroom to build the ion trap by considering all the protocols as well as their improvements for future projects.

Chapter 1

Theoretical aspect

In this chapter, we will focus on several aspects of ion trapping. First, the basis of Paul traps technology with a short demonstration of Earnshaw's theorem and its implication will be given. Then, we will discuss about the method to trap a pair of ions with opposite charges and its implementation in a modified QCCD architecture, which will finally leads to an analytical development of the interaction energy between many ions is investigated.

1.1 Paul traps

1.1.1 Earnshaw's theorem

The Earnshaw's theorem state that it is impossible to create a confining electrical potential in all direction of space with static electric fields. It comes from the first Maxwell equation (Gauss's law) in the absence of free charges $\rho = 0$.

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0} = 0 \quad (1.1)$$

Remaining the relation between electric field and electrostatic potential:

$$\vec{E} = -\vec{\nabla}V \quad (1.2)$$

Inserting this expression in equation (1.1), we obtain the Laplace's equation:

$$\nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \quad (1.3)$$

A potential is confining along one direction if its curvature is positive. The equation (1.3) shows us that, in absence of free charges, the electrostatic potential curvature can only be positive in two directions at best. For example, if $\frac{\partial^2 V}{\partial x^2}$ and $\frac{\partial^2 V}{\partial y^2}$ are positive, that mean $\frac{\partial^2 V}{\partial z^2}$ has to be negative to cancel the two first terms. In other words, an electrical potential created by statics fields cannot be confining in all directions of space.

1.1.2 Quadrupole ion traps

The quadrupole ion traps also named 'Paul traps' is one solution to have an effective trapping potential. It makes use of a radio frequency (RF) field to create radial confinement. The potential along each axes will continuously switch between confining and anti-confining according to the

electrodes polarisation as shown in figure 1.1. Using an optimal frequency allows to have only micro-oscillation of the ions around the trap center.

To easily describe the trapping, we introduce a pseudo-potential approximation. Assuming that the ions oscillate around an equilibrium, we can construct a pseudo-potential from the RF electrodes which can be used the same way than static potential to calculate the ions confinement.

Considering a particle with a charge e and a mass m , its motion in an oscillating electric field is given by:

$$m\ddot{z} = eE_0 \cos(\Omega_{rf}t) \quad (1.4)$$

According to the complete derivation done in Daniel Kienzler thesis [9]. This leads to the following expression for the pseudo-potential:

$$\Psi(\bar{z}) = \frac{eE_0^2(\bar{z})}{4m\Omega_{rf}^2} \quad (1.5)$$

Where $\Psi(\bar{z})$ is the pseudo pseudo-potential at the time averaged position $\bar{z}$, E_0 the amplitude of the electric field created by RF electrodes and Ω_{rf} the frequency of the RF electrodes.

To derive the time averaged force applied on the ions with this RF potential, we consider the pseudo-potential as a conservative electrical potential.

$$\bar{F}(\bar{z}) = -e \frac{\partial \Psi(\bar{z})}{\partial \bar{z}} \quad (1.6)$$

This result will be taken into account for the simulation in chapter 2. Indeed, the total potential can be described as the sum of a static potential created by direct current (DC) electrodes and the pseudo-potential of the radio frequency (RF) ones.

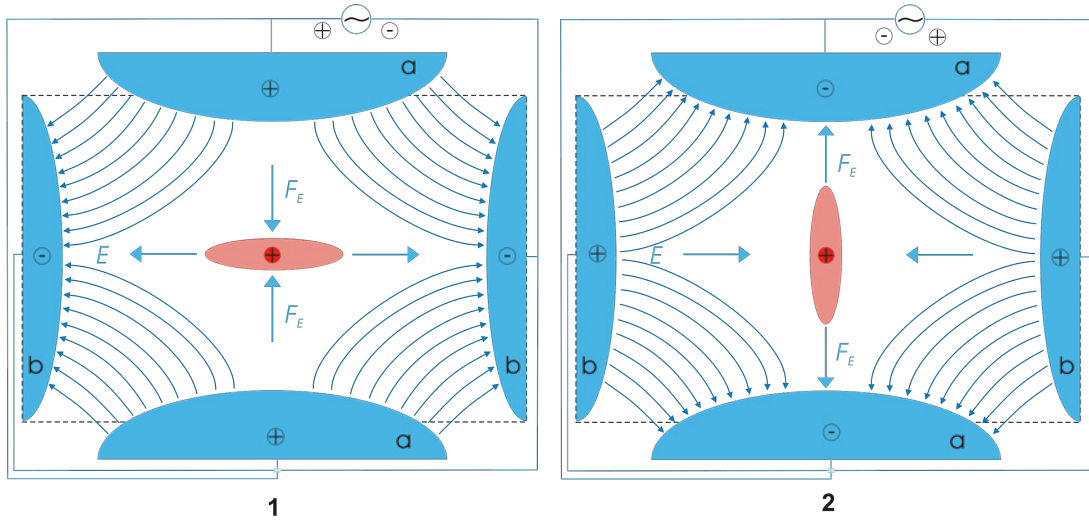


Figure 1.1: Paul trap working principle.¹

¹https://en.wikipedia.org/wiki/Quadrupole_ion_trap

1.1.3 Trapping of an ion pair with opposite charges

In order to have a first understanding of the technology explored in this work, we will discuss about the longitudinal trapping in a Paul trap and the difference coming from using a pair of ions with opposite charges instead of two positive ones. In the precedent point, the radial confinement of the ions using RF electrodes has been explained and this defines the trapping for two dimensions of space. The confinement in the third direction, along the longitudinal axis of the trap, is created by DC electrodes (constant voltage) which generate electrostatic potential wells.

Interaction between the ions occurs along the longitudinal axis of the trap. Our goal is to couple via Coulomb force two ions by bringing them close to each other, while keeping them in separated wells to avoid a collapse. Standard ion coupling experiments are performed only using positive ions because they are more stable and easier to handle. However, to couple them, a 4^{th} quadratic order DC potential shape is required as shown in the right drawing of figure 1.2. As it will be demonstrated with a simulation in chapter 2, higher quadratic orders need stronger electrode voltages.

The idea of using a negative ion in Paul trap is to decrease the DC electrical potential to the 3^{rd} quadratic order. Its shape is illustrated in the left drawing of figure 1.2. It will allow us to achieve stronger coupling by setting a smaller distance between the two ions with lower voltages than in a positive-positive configuration. We should also be able to maintain a larger ion-electrode distance for the same space between the ions (see Chapter 2). As the heating rate is directly related to the distance from the ions to the trap electrodes [9], this approach should limit the decoherence of quantum information and give some perspectives about a better scalability of the technology.

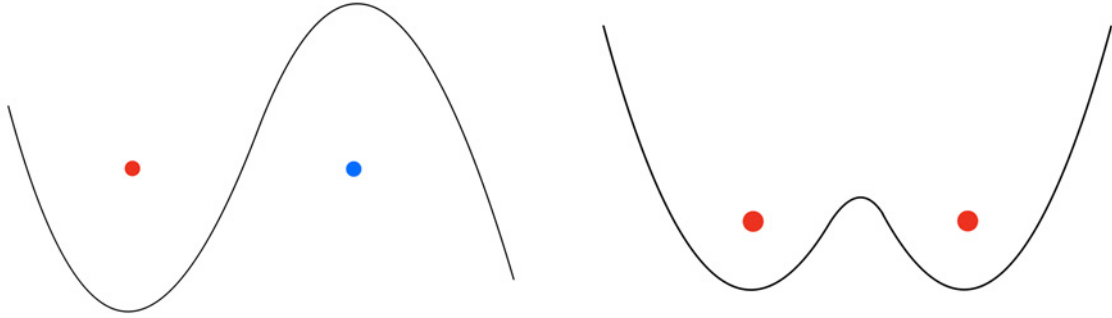


Figure 1.2: Drawing of the DC electrical potential shape for longitudinal ions trapping. The black line is a representation of the DC potential, blue point corresponds to negatively charged ion and red points to positive ones. Left: 3^{rd} order potential for trapping ions with opposite charges. Right: 4^{th} order potential for trapping two positives ions.

1.2 CNOT gate equivalent for QCCD architecture with positive and negative ions

In this section, a modified Quantum Charge-Coupled Device (QCCD) with the integration of negative ions is investigated. To create a negatively charged ion, the process consists of adding an excess electron to a specific atom. The main issue is that the bonding to the supplementary electron is weak, therefore laser cooling techniques on negative ions are difficult to achieve. One solution is to create a quantum architecture using the negative ions to encode the information and perform quantum logic operations, while using the positive ions for cooling and error correction. Indeed, if two ions have their motions coupled, they act as coupled harmonic oscillator. It results in energy exchange between the two ions over time. Cooling the first ion will therefore induce a cooling on the second one as well.

In this QCCD architecture, the negative ions are described as ‘logical qubits’ whereas the positive ions correspond to ‘ancilla qubits’. The ions choice is still in investigation, because for an optimal coupling of their motion they should have a similar mass. However, for first experiments about negative-positive ions trapping, we will use beryllium cation (Be^+), which are used in many trapped ion experiments, and deuterium anion (D^-).

The QCCD architecture consists in an array of trapped ions with alternating charge as illustrated in figure 1.3. In this drawing, blue dots correspond to negative ions which carry the quantum information and red dots to positive ions which are ancilla qubits. They are longitudinally trapped with DC electrodes that create a potential well for each ion. They can be transported along their axis with DC sequences to change the equilibrium positions of the potential.

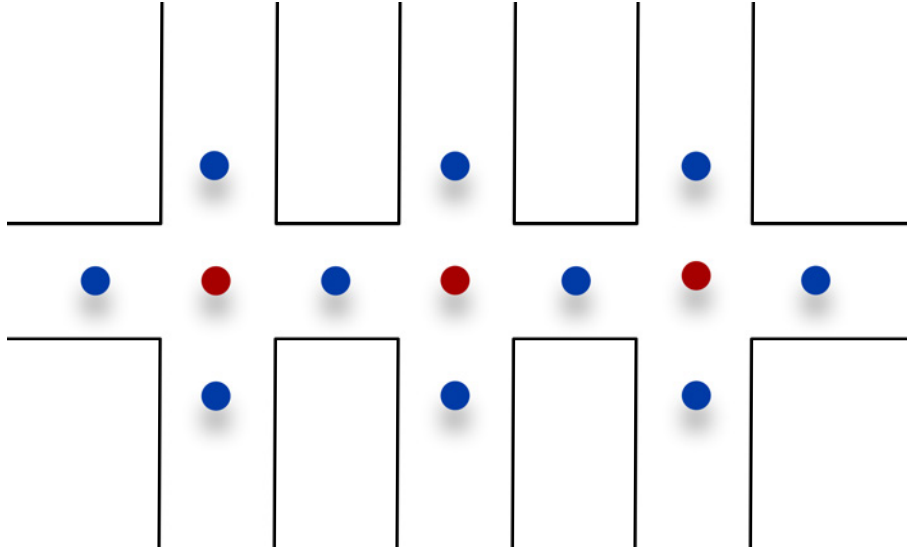


Figure 1.3: Drawing of QCCD architecture using positive (red) and negative (blue) ions.

1.2.1 Controlled-NOT (CNOT) gate with a positive ancilla

Behavior of the gate

The Controlled-NOT gate (CNOT) is one of the main components needed to build a quantum computer as it is used to entangle qubits. The symbol of the CNOT gate is shown in figure 1.4 where x is the control state and y the target. The gate mapping in z-basis is exposed in table 1.1.

Input		Output	
Control qubit	Target	Control qubit	Target
$ 0\rangle$	$ 0\rangle$	$ 0\rangle$	$ 0\rangle$
$ 0\rangle$	$ 1\rangle$	$ 0\rangle$	$ 1\rangle$
$ 1\rangle$	$ 0\rangle$	$ 1\rangle$	$ 1\rangle$
$ 1\rangle$	$ 1\rangle$	$ 1\rangle$	$ 0\rangle$

Table 1.1: Controlled-NOT gate map on the eigenstates of the z-basis.

According to its table, the behavior of the gate on eigenstates of the z-basis can be summarize as a conditional inversion of the target qubit. Indeed, only when the control qubit is at $|1\rangle$, the target switch state. In other case, the states remain unchanged after the CNOT.

However, to have a complete vision of what the gate does, it is important to consider a general superposition in input. This will determined the $|\Psi_{goal}\rangle$ to reproduce in our new architecture to have the same behavior between two negative ions.

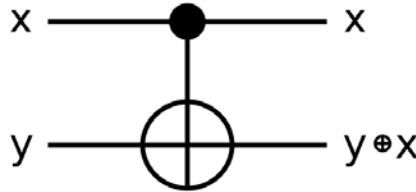


Figure 1.4: CNOT gate.

Considering the most general input on x and y :

$$|x\rangle = \alpha_1 |0\rangle + \alpha_2 |1\rangle \quad (1.7)$$

$$|y\rangle = \gamma_1 |0\rangle + \gamma_2 |1\rangle \quad (1.8)$$

The global input state can be expressed as:

$$|\Psi\rangle = (\alpha_1 |0\rangle + \alpha_2 |1\rangle) \otimes (\gamma_1 |0\rangle + \gamma_2 |1\rangle) \quad (1.9)$$

$$\Rightarrow |\Psi\rangle = \alpha_1 \gamma_1 |00\rangle + \alpha_1 \gamma_2 |01\rangle + \alpha_2 \gamma_1 |10\rangle + \alpha_2 \gamma_2 |11\rangle \quad (1.10)$$

Applying the CNOT map on the input state, it leads to a switch of probability between $|10\rangle$ and $|11\rangle$ states. The general output of this gate therefore is:

$$|\Psi_{goal}\rangle = \alpha_1 \gamma_1 |00\rangle + \alpha_1 \gamma_2 |01\rangle + \alpha_2 \gamma_1 |11\rangle + \alpha_2 \gamma_2 |10\rangle \quad (1.11)$$

Realisation in this context

The aim of this section is to find a way to reproduce the behavior of a Controlled-NOT gate (CNOT) between two negative ions, which carry the quantum information, using a positive ion as ancilla. The concept is illustrated in figure 1.5. To find the equivalent circuit, we consider a 3-qubits system where $|a\rangle$ is the state of the control qubit, $|b\rangle$ the state of the positive ancilla and $|c\rangle$ the state of the target qubit. The goal is to design a circuit which has in output the $|\Psi_{goal}\rangle$ state previously expressed between the qubits a and c . To proceed, only operations between a - b and b - c are authorized because the qubits a and c cannot be put in contact in this QCCD architecture. Furthermore, the ancilla b by definition don't handle any quantum information. Its initial state can therefore be arbitrary fixed.

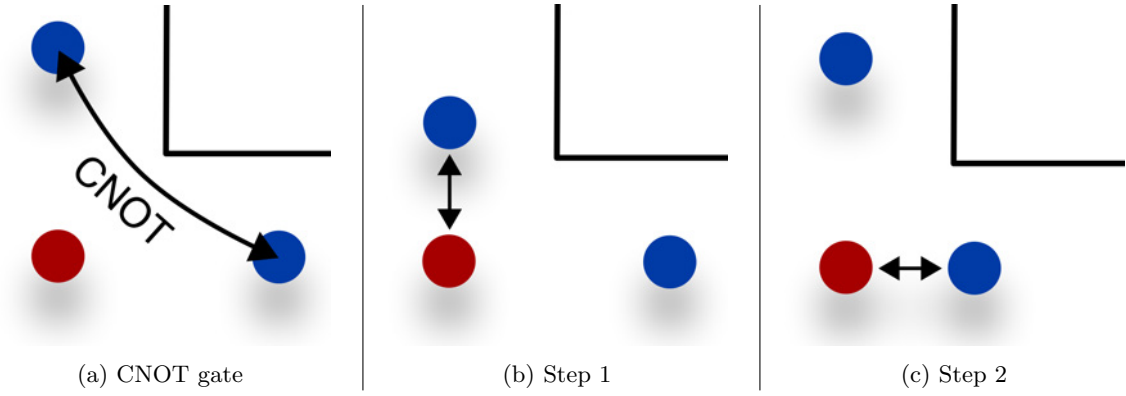


Figure 1.5: CNOT gate realization between two negative ions using a positive ion as ancilla. The goal is to achieve a CNOT gate without direct interaction between the negative ions.

1.2.2 Quantum circuit design

‘Double CNOT’ circuit analysis

A basic circuit with two CNOT gates is chosen as starting point. The qubits a and c are the two negative ions on which we would like to apply a CNOT operation using b as ancilla. The goal is to have an effective CNOT gate between $|a\rangle$ and $|c\rangle$.

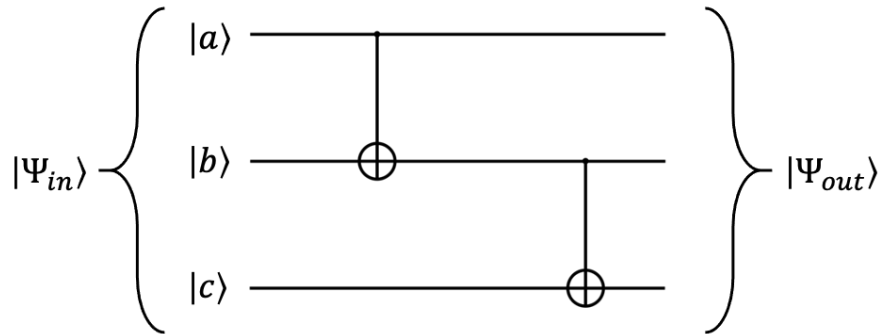


Figure 1.6: Double CNOT quantum circuit.

Starting from the most global state:

$$|a\rangle = \alpha_1 |0\rangle + \alpha_2 |1\rangle \quad (1.12)$$

$$|b\rangle = \beta_1 |0\rangle + \beta_2 |1\rangle \quad (1.13)$$

$$|c\rangle = \gamma_1 |0\rangle + \gamma_2 |1\rangle \quad (1.14)$$

We can write the initial state:

$$|\Psi\rangle = (\alpha_1 |0\rangle + \alpha_2 |1\rangle) \otimes (\beta_1 |0\rangle + \beta_2 |1\rangle) \otimes (\gamma_1 |0\rangle + \gamma_2 |1\rangle) \quad (1.15)$$

We develop:

$$\begin{aligned} |\Psi\rangle = & \alpha_1 \beta_1 \gamma_1 |000\rangle + \alpha_1 \beta_1 \gamma_2 |001\rangle + \alpha_1 \beta_2 \gamma_1 |010\rangle + \alpha_1 \beta_2 \gamma_2 |011\rangle + \\ & \alpha_2 \beta_1 \gamma_1 |100\rangle + \alpha_2 \beta_1 \gamma_2 |101\rangle + \alpha_2 \beta_2 \gamma_1 |110\rangle + \alpha_2 \beta_2 \gamma_2 |111\rangle \end{aligned}$$

Applying the first CNOT gate:

$$|\Psi_1\rangle = CNOT_{a,b} \otimes Id_c |\Psi\rangle \quad (1.16)$$

We obtain:

$$\begin{aligned} |\Psi_1\rangle = & \alpha_1 \beta_1 \gamma_1 |000\rangle + \alpha_1 \beta_1 \gamma_2 |001\rangle + \alpha_1 \beta_2 \gamma_1 |010\rangle + \alpha_1 \beta_2 \gamma_2 |011\rangle + \\ & \alpha_2 \beta_1 \gamma_1 |110\rangle + \alpha_2 \beta_1 \gamma_2 |111\rangle + \alpha_2 \beta_2 \gamma_1 |100\rangle + \alpha_2 \beta_2 \gamma_2 |101\rangle \end{aligned}$$

Applying the second CNOT gate:

$$|\Psi_{out}\rangle = Id_a \otimes CNOT_{b,c} |\Psi_1\rangle \quad (1.17)$$

We obtain:

$$\begin{aligned} |\Psi_{out}\rangle = & \alpha_1 \beta_1 \gamma_1 |000\rangle + \alpha_1 \beta_1 \gamma_2 |001\rangle + \alpha_1 \beta_2 \gamma_1 |011\rangle + \alpha_1 \beta_2 \gamma_2 |010\rangle + \\ & \alpha_2 \beta_1 \gamma_1 |111\rangle + \alpha_2 \beta_1 \gamma_2 |110\rangle + \alpha_2 \beta_2 \gamma_1 |100\rangle + \alpha_2 \beta_2 \gamma_2 |101\rangle \end{aligned}$$

At this point we would like to have a more friendly expression of $|\Psi_{out}\rangle$ to figure out what are the next operations to perform.

$$\begin{aligned} |\Psi_{out}\rangle = & \beta_1 (|0_b\rangle + |1_b\rangle) \otimes (\alpha_1 \gamma_1 |0_a 0_c\rangle + \alpha_1 \gamma_2 |0_a 1_c\rangle + \alpha_2 \gamma_1 |1_a 1_c\rangle + \alpha_2 \gamma_2 |1_a 0_c\rangle) \\ & + \beta_2 (|0_b\rangle - |1_b\rangle) \otimes (\alpha_1 \gamma_1 |0_a 1_c\rangle + \alpha_1 \gamma_2 |0_a 0_c\rangle + \alpha_2 \gamma_1 |1_a 0_c\rangle + \alpha_2 \gamma_2 |1_a 1_c\rangle) \\ & - \beta_1 |0_b\rangle \otimes (\alpha_2 \gamma_1 |1_a 1_c\rangle + \alpha_2 \gamma_2 |1_a 0_c\rangle) \\ & - \beta_1 |1_b\rangle \otimes (\alpha_1 \gamma_1 |0_a 0_c\rangle + \alpha_1 \gamma_2 |0_a 1_c\rangle) \\ & - \beta_2 |0_b\rangle \otimes (\alpha_1 \gamma_1 |0_a 1_c\rangle + \alpha_1 \gamma_2 |0_a 0_c\rangle) \\ & - \beta_2 |1_b\rangle \otimes (\alpha_2 \gamma_1 |1_a 0_c\rangle + \alpha_2 \gamma_2 |1_a 1_c\rangle) \end{aligned}$$

Proceeding this way, we easily find the iterations of $|\Psi_{goal}\rangle$ in our global expression. We can therefore rewrite this expression in x-basis for $|b\rangle$.

$$\begin{aligned}
 |\Psi_{out}\rangle = & \sqrt{2}\beta_1 |+_b\rangle \otimes |\Psi_{goal}\rangle \\
 & + \sqrt{2}\beta_2 |-_b\rangle \otimes (Id_a \otimes X_c |\Psi_{goal}\rangle) \\
 & - \frac{\beta_1}{\sqrt{2}} (|+_b\rangle + |-_b\rangle) \otimes (\alpha_2\gamma_1 |1_a1_c\rangle + \alpha_2\gamma_2 |1_a0_c\rangle) \\
 & - \frac{\beta_1}{\sqrt{2}} (|+_b\rangle - |-_b\rangle) \otimes (\alpha_1\gamma_1 |0_a0_c\rangle + \alpha_1\gamma_2 |0_a1_c\rangle) \\
 & - \frac{\beta_2}{\sqrt{2}} (|+_b\rangle + |-_b\rangle) \otimes (\alpha_1\gamma_1 |0_a1_c\rangle + \alpha_1\gamma_2 |0_a0_c\rangle) \\
 & - \frac{\beta_2}{\sqrt{2}} (|+_b\rangle - |-_b\rangle) \otimes (\alpha_2\gamma_1 |1_a0_c\rangle + \alpha_2\gamma_2 |1_a1_c\rangle)
 \end{aligned}$$

Since $|b\rangle$ is the state of an ancilla, this qubit don't carry any quantum information and its initial state can be arbitrary chosen. In other word, the values β_1 and β_2 can be fixed at our convenience. The only constraint is to have a normalized state. We therefore use the following values to simplify our sate expression:

$$\beta_1 = 1, \beta_2 = 0 \quad (1.18)$$

This leads to a simplified expression of the output state $|\Psi_{out}\rangle$:

$$\begin{aligned}
 |\Psi_{out}\rangle = & \sqrt{2} |+_b\rangle \otimes |\Psi_{goal}\rangle \\
 & - \frac{1}{\sqrt{2}} (|+_b\rangle + |-_b\rangle) \otimes (\alpha_2\gamma_1 |1_a1_c\rangle + \alpha_2\gamma_2 |1_a0_c\rangle) \\
 & - \frac{1}{\sqrt{2}} (|+_b\rangle - |-_b\rangle) \otimes (\alpha_1\gamma_1 |0_a0_c\rangle + \alpha_1\gamma_2 |0_a1_c\rangle)
 \end{aligned}$$

1.2.3 Measurement in x-basis on qubit b

At this point, a measurement on b in x-basis would be a suitable way to simply our state. As reminder, performing a measurement will leads to a random collapse of the qubit on one of its eigenstates. In this case $|+_b\rangle$ or $|-_b\rangle$. It also means that all the contribution from the other eigenstates will be removed from the expression. Therefore, there are two cases to treat corresponding to the two possibilities of collapse.

Collapsing in $|+_b\rangle$

Let us first consider the case where the measurement gives $|+_b\rangle$ as result. We therefore apply the projector:

$$|\Psi_{out}\rangle \longrightarrow |\Psi_{m+}\rangle = |+_b\rangle \langle+_b| \Psi_{out}\rangle \quad (1.19)$$

We find:

$$|\Psi_{m+}\rangle = |+_b\rangle \otimes \left(\sqrt{2} |\Psi_{goal}\rangle - \frac{1}{\sqrt{2}} (\alpha_2 \gamma_1 |1_a 1_c\rangle + \alpha_2 \gamma_2 |1_a 0_c\rangle + \alpha_1 \gamma_1 |0_a 0_c\rangle + \alpha_1 \gamma_2 |0_a 1_c\rangle) \right) \quad (1.20)$$

We can see that the right-hand part of (1.20) is also equal to $|\Psi_{goal}\rangle$. The expression can be reduced:

$$|\Psi_{m+}\rangle = \frac{1}{\sqrt{2}} |+_b\rangle \otimes |\Psi_{goal}\rangle \quad (1.21)$$

We conclude that if the state of b collapse in $|+_b\rangle$, we directly obtain the goal state for the qubits a and c .

Collapsing in $|-_b\rangle$

Let us now consider the case where the measurement gives $|-_b\rangle$ as result. We therefore apply the projector:

$$|\Psi_{out}\rangle \longrightarrow |\Psi_{m-}\rangle = |-_b\rangle \langle -_b | \Psi_{out}\rangle \quad (1.22)$$

We find:

$$|\Psi_{m-}\rangle = |-_b\rangle \otimes \frac{1}{\sqrt{2}} (\alpha_1 \gamma_1 |0_a 0_c\rangle + \alpha_1 \gamma_2 |0_a 1_c\rangle - \alpha_2 \gamma_1 |1_a 1_c\rangle - \alpha_2 \gamma_2 |1_a 0_c\rangle) \quad (1.23)$$

In this case, we don't directly find the $|\Psi_{goal}\rangle$ state. However, we can see in (1.23) that applying a sign inversion on α_2 would allow us to find $|\Psi_{goal}\rangle$. This operation correspond to a "Z" gate applied on the qubit a .

1.2.4 Final circuit

From the previous point, we saw that a measurement performed in x-basis on b qubit followed by a conditional 'Z' gate would allow us to have a complete CNOT equivalence between a and c . The final circuit resulting from the previous calculations is shown in figure 1.7.

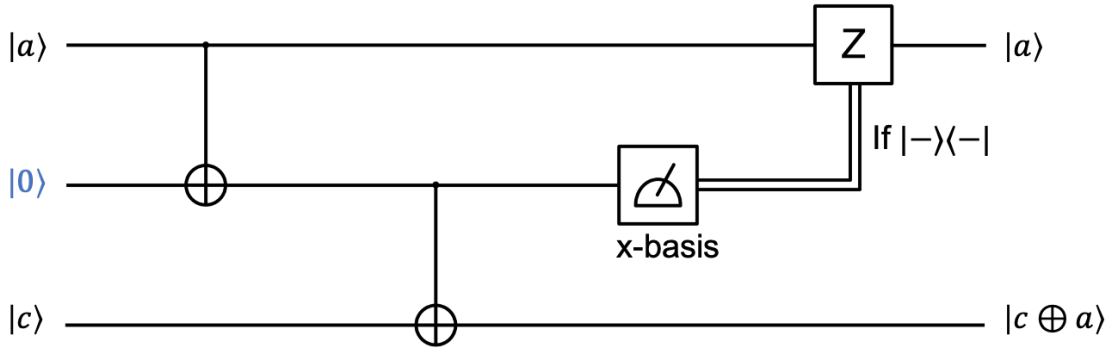


Figure 1.7: Complete CNOT equivalent circuit between qubits a and c .

1.3 Energy transfer for many ions

An interesting calculation to proceed is to know the coupling by Coulomb interaction of our trapped ions. At its first time of use, the trap will catch several ions in both sides before going in single ion regime. Working first with many ions is easier to study because it allows stronger coupling and the ion loss will less matter. Therefore, we would like to describe the energy of interaction in function of the number of positive and negative ions and their equilibrium distance. In this section, an analytical expression of this coupling is derived.

1.3.1 Analytical development

Position of cold ions in an harmonic potential

We assume that the ions align along the longitudinal direction due to strong confinement in others. We can use the formula derived in the paper of Todd P. Meyrath [10] as ions equilibrium position.

$$x_n = \left(\frac{e^2}{4\pi\epsilon_0 m\omega_x^2} \right)^{\frac{1}{3}} \alpha(N) \sin \left(\frac{1}{3} \sin^{-1} \left(\beta(N) \left[n - \frac{N+1}{2} \right] \right) \right) \quad (1.24)$$

Where N is the number of ion trapped in the harmonic potential, x_n the position of the n^{th} ion and $\alpha(N)$, $\beta(N)$ are constants depending on N .

To simplify, we can neglect the effect at the edges of the harmonic potential and having a linear distribution of the ion using $\sin \left(\frac{1}{3} \sin^{-1} (x) \right) \approx \frac{x}{3}$. Finally we obtain:

$$x_n = A(N)n + B(N) \quad (1.25)$$

with:

$$A(N) = \left(\frac{e^2}{4\pi\epsilon_0 m\omega_x^2} \right)^{\frac{1}{3}} \alpha(N)\beta(N), \quad B(N) = -\frac{N+1}{2}A(N)$$

Double well positive-negative ions coupling

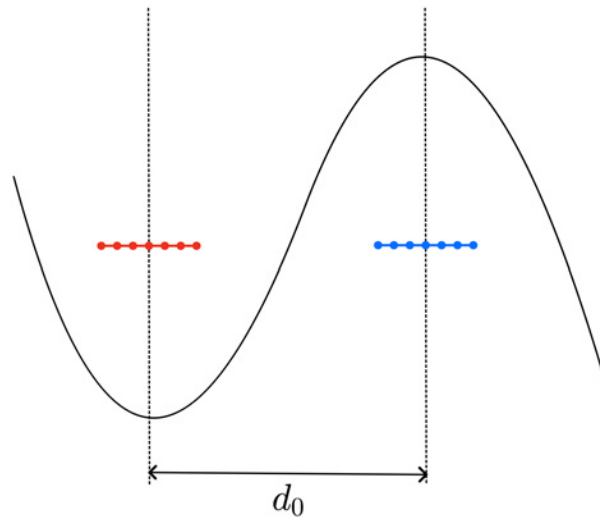


Figure 1.8: Illustration of multiple ions trapped in longitudinal DC electrical potential. Red: positive ion string. Blue: negative ion string.

The total coulomb potential for multiple charges is:

$$U_E = \frac{-e^2}{8\pi\epsilon_0} \sum_{n=1}^N \sum_{l=1}^L \frac{1}{d(n,l)} \quad (1.26)$$

With $d(n,l)$ the distance between the n^{th} positive and the l^{th} negative ion. Considering $x_{pos}(n)$ and $x_{neg}(l)$ as the position of the two ions in their potential well, we can express:

$$d(n,l) = d_0 - x_{pos}(n) + x_{neg}(l) = d_0 (1 - (x_{pos}(n) - x_{neg}(l)) / d_0) \quad (1.27)$$

Multipole expansion:

$$U_E \approx \frac{-e^2}{8\pi\epsilon_0 d_0} \sum_{n=1}^N \sum_{l=1}^L \left(1 + \frac{x_{pos}(n) - x_{neg}(l)}{d_0} + \left(\frac{x_{pos}(n) - x_{neg}(l)}{d_0} \right)^2 \right) \quad (1.28)$$

The position of each positive and negative ion can be considered has a variation around their equilibrium position in each wells (defined before). Naming x_a and x_b the oscillations of respectively positive and negative ions and x_n , x_l their equilibrium position.

$$\begin{cases} x_{pos}(n) = x_n + x_a \\ x_{neg}(l) = x_l + x_b \end{cases}$$

Developing equation (1.28), we obtain the following Hamiltonian:

$$H = \frac{-e^2}{8\pi\epsilon_0 d_0} \sum_{n=1}^N \sum_{l=1}^L \left(1 + \frac{x_{pos}(n)}{d_0} - \frac{x_{neg}(l)}{d_0} + \frac{x_{pos}(n)^2}{d_0^2} + \frac{x_{neg}(l)^2}{d_0^2} - \frac{2x_{pos}(n)x_{neg}(l)}{d_0^2} \right) \quad (1.29)$$

We would like to work in an interaction picture by isolating only the interaction term of the Hamiltonian: $H = H_0 + H_{int}$. According to the previous development, only the last term describes an interaction between the positive and negative ions.

$$H_{int} = \frac{e^2}{8\pi\epsilon_0 d_0^3} \sum_{n=1}^N \sum_{l=1}^L x_{pos}(n)x_{neg}(l) \quad (1.30)$$

Inserting the expression of $x_{pos}(n)$ and $x_{neg}(l)$,

$$H_{int} = \frac{e^2}{4\pi\epsilon_0 d_0^3} \sum_{n=1}^N \sum_{l=1}^L x_n x_l + x_n x_b + x_a x_l + x_a x_b \quad (1.31)$$

At this stage we can consider the position x_a and x_b as quantum positions operator in an harmonic potential. Indeed, these terms corresponds to oscillations of the positive (respectively negative) ions in there potential well. These wells are approximated as harmonic potential around equilibrium. Recalling the quantum operator of the position in harmonic potential, we expressed:

$$\hat{x}_a = \sqrt{\frac{\hbar}{2m\omega}} (\hat{a} + \hat{a}^\dagger) \quad (1.32)$$

$$\hat{x}_b = \sqrt{\frac{\hbar}{2m\omega}} (\hat{b} + \hat{b}^\dagger) \quad (1.33)$$

Where $\hat{a}$, $\hat{a}^\dagger$ and $\hat{b}$, $\hat{b}^\dagger$ are creation and annihilation operators of the harmonic potential wells respectively confining positive and negative ions.

We obtain:

$$H_{int} = \frac{e^2}{4\pi\epsilon_0 d_0^3} \sum_{n=1}^N \sum_{l=1}^L x_n x_l + x_n \sqrt{\frac{\hbar}{2m_b\omega_b}} (\hat{b} + \hat{b}^\dagger) + x_l \sqrt{\frac{\hbar}{2m_a\omega_a}} (\hat{a} + \hat{a}^\dagger) + \frac{\hbar}{2\sqrt{m_a m_b \omega_a \omega_b}} (\hat{a} + \hat{a}^\dagger) (\hat{b} + \hat{b}^\dagger) \quad (1.34)$$

Once gain, we would like to consider only the interaction part to have a description of the energy exchanged between the positive and negative ions. That means, we can remove all the terms where only $\hat{a}$ (and $\hat{a}^\dagger$) or $\hat{b}$ (and $\hat{b}^\dagger$) are considered. We can now express our coupling:

$$H_{int} = \hbar\Omega_{ex} (\hat{a} + \hat{a}^\dagger) (\hat{b} + \hat{b}^\dagger) \quad (1.35)$$

With the following formula for the energy exchange frequency:

$$\Omega_{ex} = \frac{NLe^2}{8\pi\epsilon_0 d_0^3 \sqrt{m_a m_b \omega_a \omega_b}} \quad (1.36)$$

Discussion

An interesting comparison can be done with the formula of the interaction between two single ions in separate harmonic potential wells. We can find it in several papers as the one of A. C. Wilson [11] or M. Harlander's et al. paper [12] in which the coupling with many ions also is investigated. The exchange frequency for single ion in separate potential wells is:

$$\Omega_{ex} = -\frac{q_a q_b}{4\pi\epsilon_0 d_0^3 \sqrt{m_a m_b \omega_a \omega_b}} \quad (1.37)$$

If we compare this expression to our result (1.36), where ions with charge $q_1 = -q_2 = e$ has been considered, we see that our result is similar to (1.37) with a factor on the charges depending on the number of trapped ions.

Chapter 2

Planar Trap Simulation

The aim of this chapter is to compare negative-positive ion trap to the currently used positive-positive ones. This will be achieved by simulating a planar trap geometry in Mathematica and optimizing the design in both cases. The two following situations will be used for the comparison:

- 1 MHz trap frequency, distance between ions of 20 μm , distance from trap surface: 100 μm
- 3 MHz trap frequency, distance between ions of 10 μm , distance from trap surface: 50 μm

The choice of these configurations is based on an educated guess from my supervisor that these parameters might work fine. In the first case, the ions sit far from the DC electrodes (100 μm) in comparison to the distance between them. This configuration is interesting since anomalous heating scale as $\sim d^{-4}$ with d the distance of the ion to the trap electrodes [9]. The second configuration considers a higher trap frequency to bring the ions closer to each other. It would improve the coupling of the ions by Coulomb interaction. In both cases, the main limitation for the positive-positive ion trap is that very high voltages are required to achieved these configurations. As we want to minimise the distance between the DC electrodes, high voltages imply a limitation due to breakdown voltage of the dielectric material insulating them.

In this section, the benefit of using negative-positive ion trap is investigated by optimizing the design of a planar trap and simulating the generated DC potential. The simulation is done with Mathematica using *SurfacePatern.m* package of Roman Schmied [13].

2.1 Planar trap design

Figure 2.1 shows the basic design of the simulation. It is based on Florian Leupold's thesis [14]. The length of the DC and RF electrodes are voluntary very long (cut on the figures) to remove edge effects in the simulation and the non-used area (gray zones) are explicitly grounded. In the case of negative-positive ion traps (Fig. 2.1a), four electrodes are required. This is can be intuitively understood by the fact that the negative and positive ions will sit in front of positive and negative electrodes, respectively. However, in the case of two positive ions (Fig. 2.1b), a central electrode with positive voltage is need to separate the two potential wells. This lead to a total of five DC electrodes. In this drawing, the purple electrodes correspond to RF voltage and would confine the ions in Y and Z direction. The red and blue areas describe respectively positive and negative DC electrodes.

After running the simulation for positive-positive ion trap, we noticed that the simulation used the grounded plates (gray areas), on the sides, to calculate the electrostatic trapping potential generated by the DC electrodes. This was problematic because we would like to optimise the trap geometry by considering our five electrodes without additional contribution. Indeed, in a QCCD architecture with many ions, the gray areas will be filled with additional sets of electrodes to trap other ions. A different design (Fig. 2.2) has therefore been used to optimize the voltage without taking grounded parts into account. Please notice that this new design finally gave pretty similar results since the optimisation algorithm found that the external electrodes must be grounded to minimise the voltage (Table 2.2 in section 2.2.3).

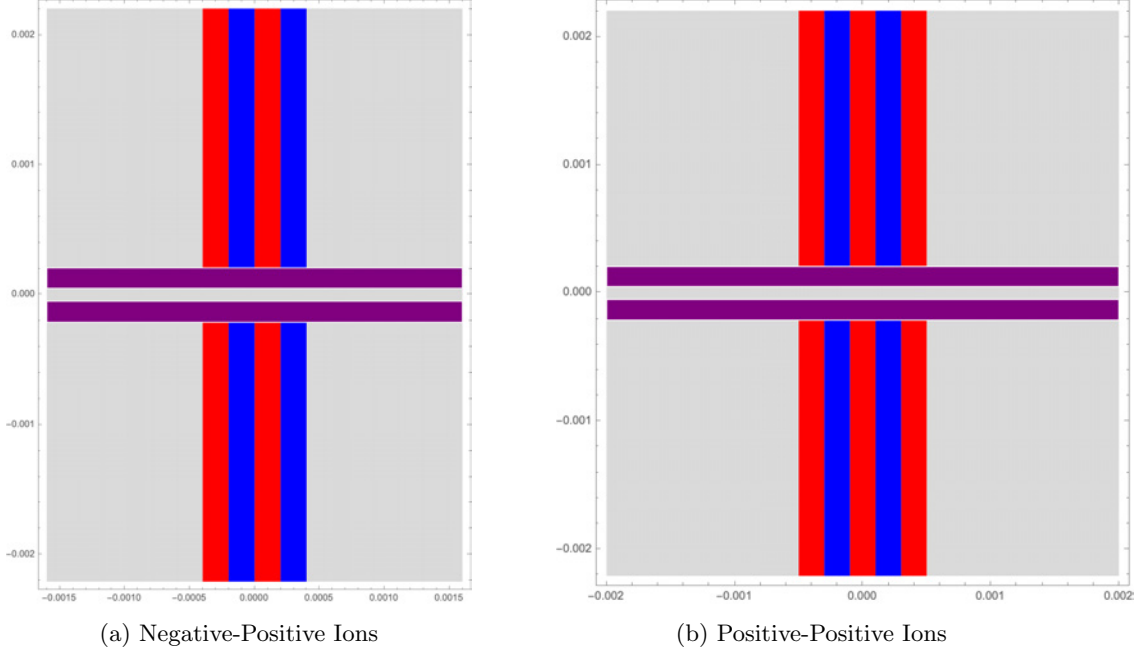


Figure 2.1: Basic design for planar trap simulation. Blue: Negative voltage, Red: Positive voltage, Gray: ground, Purple: RF voltage.

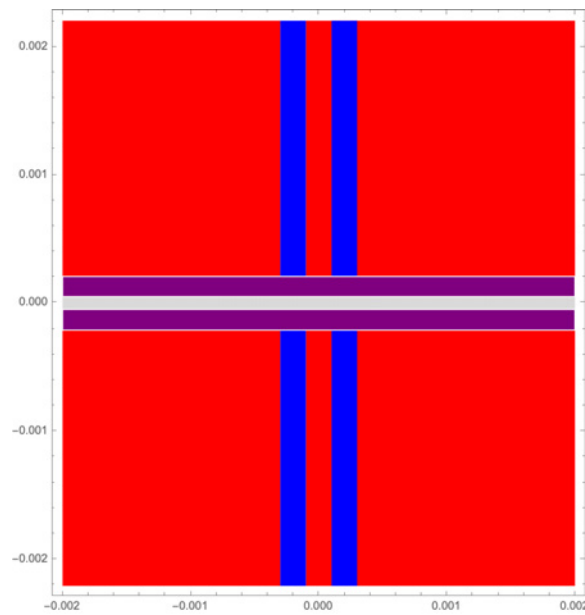


Figure 2.2: Positive-Positive ion trap basic design without side grounded electrode.

2.1.1 RF electrodes optimisation

The RF electrodes produce the pseudo-potential which confine the ion in the direction where DC field is anti-confining. As detailed in the precedent chapter, Laplace equation $\nabla^2\Phi = 0$ informed us that a static electric field cannot create a trapping potential in all direction of space. A dynamic potential is needed and is created by RF electrodes in the context of a Paul trap. This dynamic potential can be approximate as a pseudo-potential:

$$\Phi_{pseudo}(\mathbf{x}) = \frac{eE_0^2(\mathbf{x})}{m\Omega_{rf}^2} \quad (2.1)$$

Where $E_0(\mathbf{x})$ is the electric field amplitude at a position $\mathbf{x}$ in space, m the ion mass, e the ion charge and Ω_{rf} the RF voltage frequency.

The width of RF electrodes must be designed in a way to have the ions at the chosen distance from electrodes and with the strongest confinement in all directions. In the case of a planar trap, the confinement in vertical direction is the weakest. The idea here is to find a design for RF electrodes which create the deepest pseudo-potential in z . Two parameters are taken into account:

- The ratio between the width of RF electrodes and the central ground
- The width of the central ground electrode

In this section, no comparison are done between negative-positive and positive-positive ion traps because the RF electrode design is the same in both cases.

2.1.2 Trap Depth in z-direction optimization

The trap depth is defined in this simulation as the potential difference between the local minimum and the next local maximum along the chosen axis of the electric potential. It therefore correspond to the minimal energy the ion would need to escape from the trap. As part of the optimisation, the focus is done on the vertical (z) axis. The reason is that a planar trap has a much stronger confinement in radial direction than in the vertical one as shown in figures 2.5 and 2.6.

Width Ratio between RF and GND electrodes

In figure 2.3, the trap depth dependence to the RF/ground(GND) width ratio is investigated for different ground width. For each curve, we find a maximum at 119%. This value does not depend on the ground width. Please notice that for this simulation very long RF electrodes are used to neglect edges effect. In case of short RF electrodes the optimal ratio start to be influenced by the ground width. The problematic of surface-electrode geometry optimisation for Paul traps is also analytically investigated in the publication of J. H. Wesenberg [15].

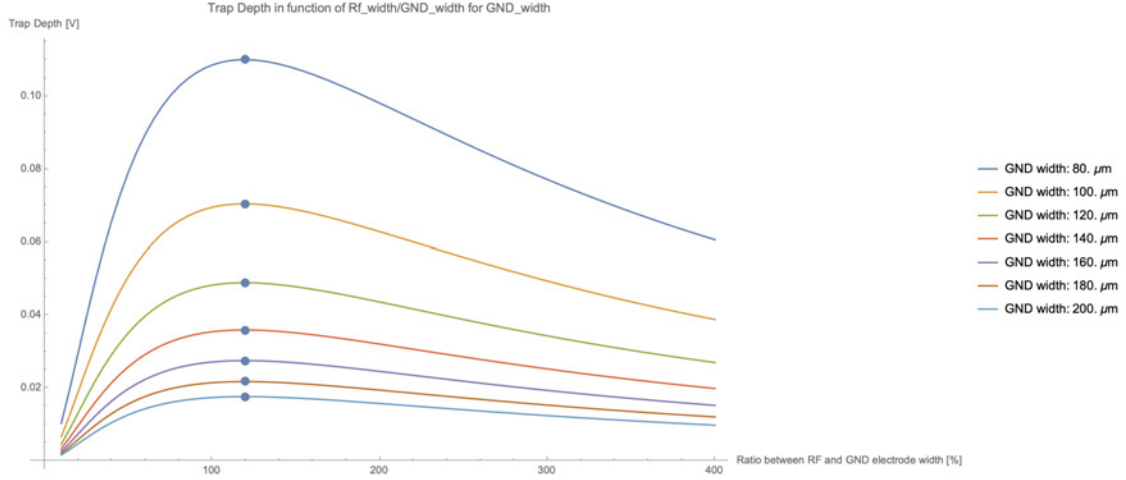
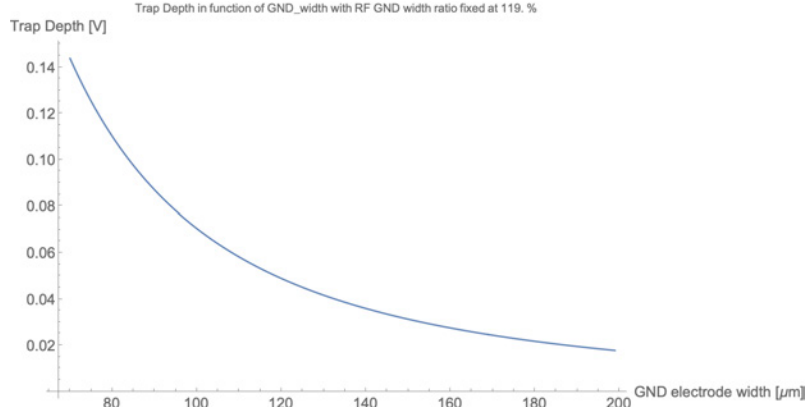


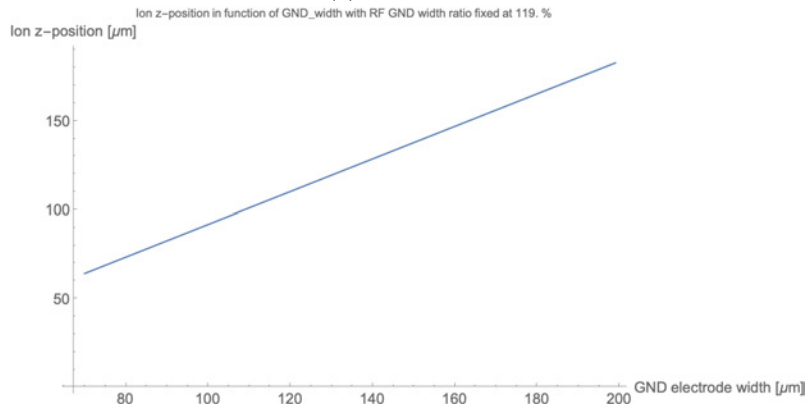
Figure 2.3: Trap depth in function of RF/GND electrodes width ratio for different GND width.

GND electrode width

For a fixed ratio between RF and GND electrodes width, the dependence on GND electrode width is investigated (Fig. 2.4). The plots show that increasing the ground electrode width allows a higher z-position for the ion but decrease the trap depth. It explains the pseudo-potential shape differences visible in figure 2.6 between the 1 MHz and 3 MHz trap parameters.



(a) Trap depth



(b) Ion z-position

Figure 2.4: Trap depth and ion z-position in function of ground electrode width using optimal RF/GND width ratio.

Optimal design

Numerically finding the ground width for our two configurations (distance from surface electrodes of 100 μm for the 1 MHz trap and 50 μm for the 3 MHz), we obtain the results of table 2.1.

Electrode voltage	Ion z-position	GND width	RF width	Ratio	Trap depth
100 V	100.2 μm	109 μm	129.7 μm	119 %	59 mV
	50.6 μm	55 μm	65.5 μm	119 %	233 mV

Table 2.1: Design parameter found from pseudo-potential optimisation in z-direction.

Pseudo-potential calculation

In figures 2.5 and 2.6, the pseudo-potential generated by RF electrodes after optimisation is plotted along Y and Z axis. As expected, the trap potential is in all cases much deeper in Y than Z direction. A density plot is also realized in figure 2.7. The pseudo-potential has constant values along the black lines and its intensity is described by a color pattern: orange corresponds to highest potential value and blue to the lowest. The red dot indicates the trapped ion equilibrium position.

In both cases the potential is calculated at the center of the trap design ($x=0$ according to Fig.2.1). This makes the ‘edge effect’ negligible since the calculation is done far from the ends of the RF electrodes. This consideration is based on the idea that in a complete quantum charge-coupled device (QCCD) architecture, the RF electrodes are much longer than the DC electrodes for one pair of ions.

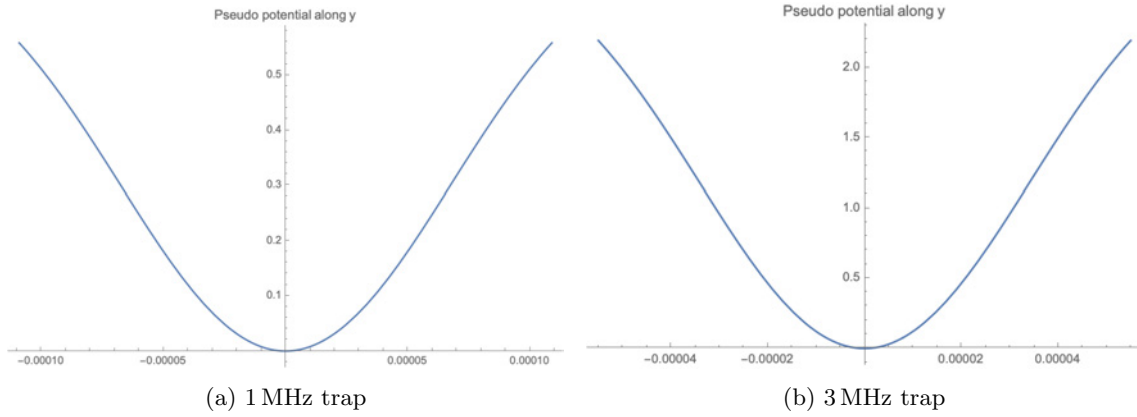


Figure 2.5: Pseudo-potential along y-axis generated by the RF optimal electrodes design. Potential calculated at the z-position of the ion and at $x=0$ (corresponding to the middle of RF electrodes) to not see edge effect in the simulation.

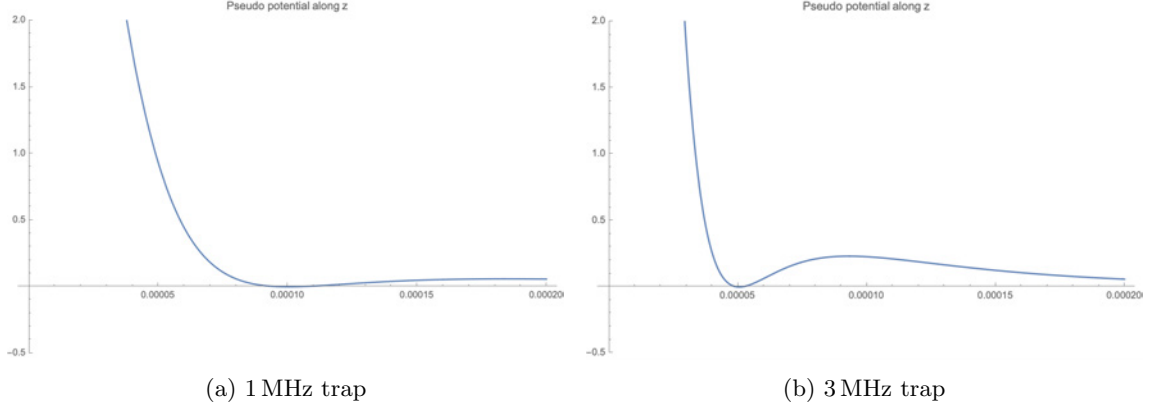


Figure 2.6: Pseudo-potential along z-axis generated by the RF optimal electrode design. Potential calculated at $y=0$ and $x=0$ (corresponding to the center of the trap design) to not see edge effect in the simulation.

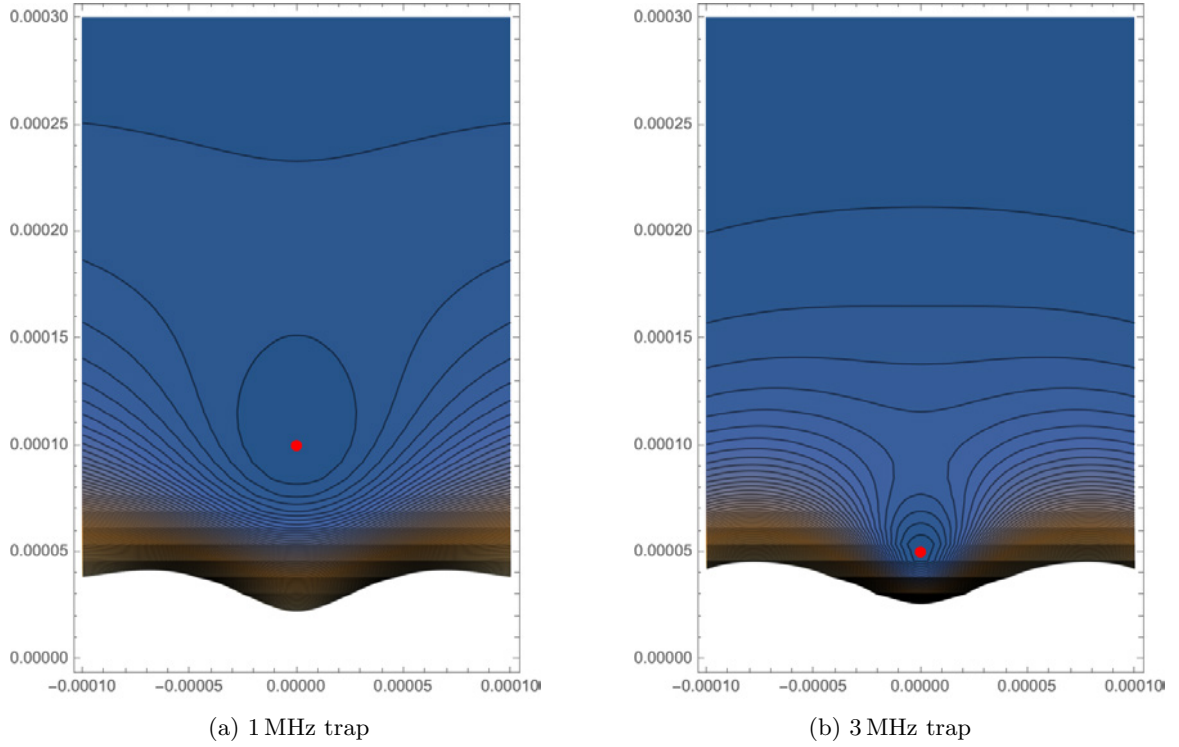


Figure 2.7: Density plot of the pseudo-potential in YZ plane generated by the RF optimal electrode design. The calculation is done at $x = 0$ (middle of RF electrodes) to not see edge effect in the simulation.

2.2 DC electrodes width optimisation

The DC electrodes width can be optimized to minimize the applied voltage. To succeed in this optimisation, constraints on the potential in x-direction must be expressed. This will be the main criterion in the comparison between negative-positive and positive-positive ion trap.

For the two technologies in both cases (1 and 3 MHz trap), the DC voltage required to create a trapping potential in function of the electrodes width is investigated. The optimal width is defined as the one which minimize the sum of squared voltages. From the symmetries of the trapping

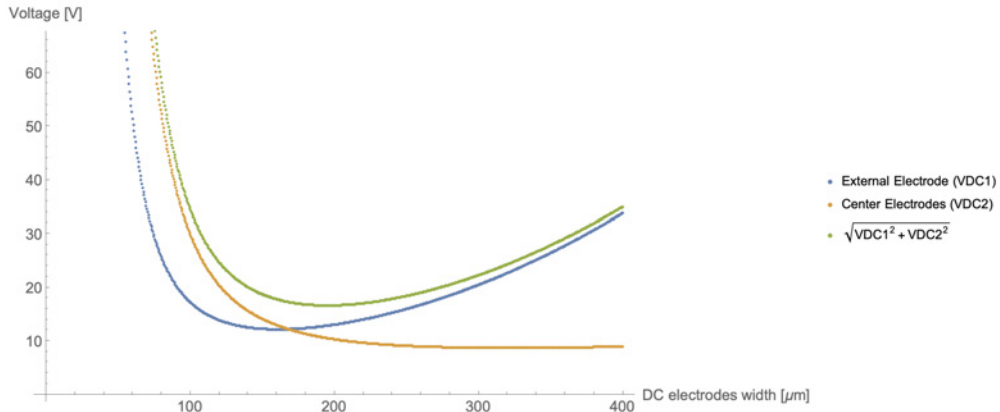
potential, we can reduce the number of voltage variables to two for the negative-positive trap (red and blue electrodes, Fig. 2.1) and three for the positive-positive trap (red and blue external electrodes and the central one, Fig. 2.2) .

2.2.1 Negative-Positive ion trap

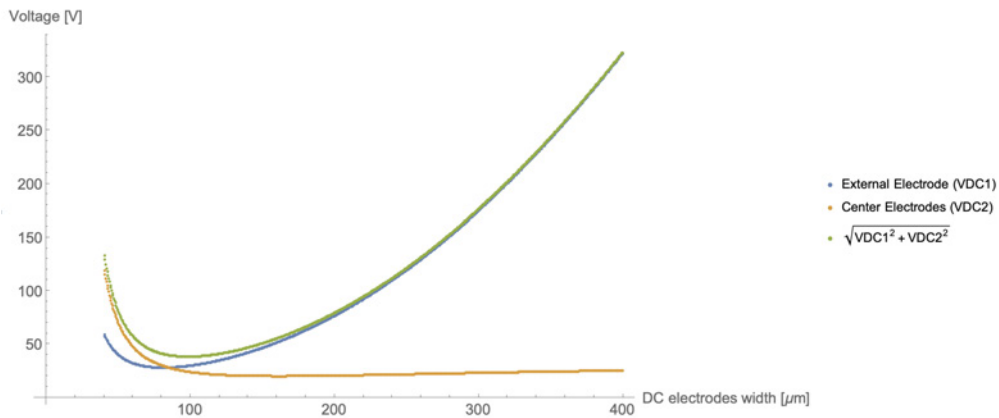
In the case of Negative-Positive ion trap, we have two variables named VDC_1 and VDC_2 corresponding to the absolute value of the voltage applied on respectively external and internal electrode pair. The system of equations to solve is the following:

$$\begin{cases} \partial_x \Phi_{DC}(d/2, 0, z_{ion}) &= 0 \\ \partial_x \Phi_{DC}(-d/2, 0, z_{ion}) &= 0 \\ \partial \partial_x \Phi_{DC}(d/2, 0, z_{ion}) &= -a \\ \partial \partial_x \Phi_{DC}(-d/2, 0, z_{ion}) &= a \end{cases} \quad (2.2)$$

Where d is the distance between the ions (20 μm or 10 μm respectively for 1 and 3 MHz trap) and z_{ion} is the vertical position of the ion (100 μm or 50 μm respectively for 1 and 3 MHz trap). a correspond to the curvature needed for the trapping at each equilibrium position and is defined according to D. Kienzler Thesis [9] as $a = m(2\pi f_{trap})/e$. The result of this system in function of the DC electrodes width is plotted in figure 2.8.



(a) 1 MHz trap



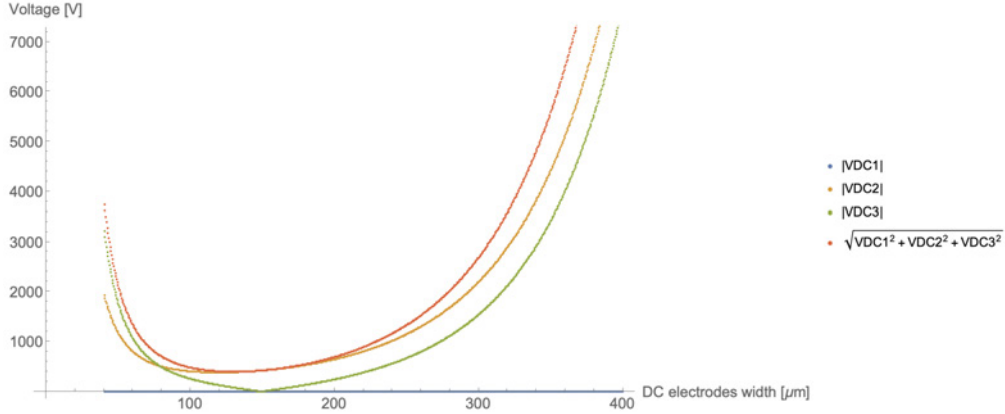
(b) 3 MHz trap

Figure 2.8: Voltage required on DC electrodes to trap negative and positive ions at a distance of 10 μm and 20 μm , respectively for 3 MHz and 1 MHz, trap in function to the electrode width.

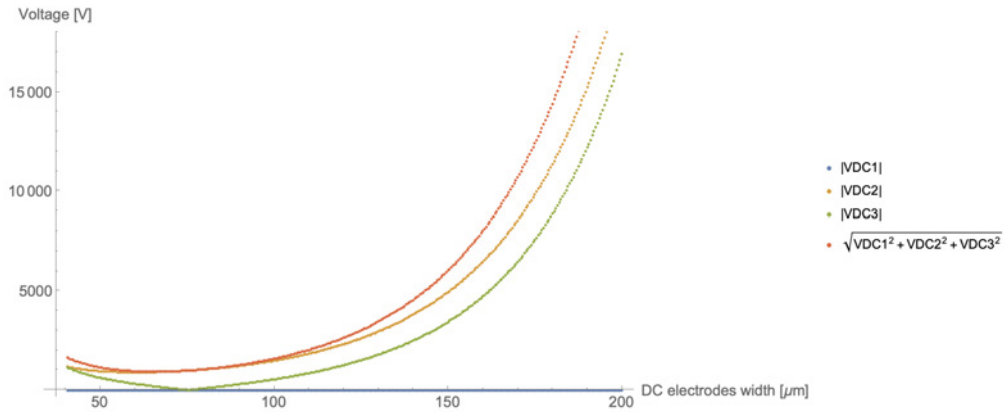
2.2.2 Positive-Positive ion trap

In the case of positive-positive ion trap, three different voltages have to be taken into account. The voltage on external electrodes (large red in Fig. 2.2), the two internal electrodes (blue in Fig. 2.2) and the center electrode. We label these voltages respectively VDC_1 , VDC_2 and VDC_3 . One constraint is added at $x = 0$ to have a local maximum and the curvature for the two ions position should have the same sign.

$$\begin{cases} \partial_x \Phi_{DC}(d/2, 0, z_{ion}) &= 0 \\ \partial_x \Phi_{DC}(-d/2, 0, z_{ion}) &= 0 \\ \partial_x \Phi_{DC}(0, 0, z_{ion}) &= 0 \\ \partial \partial_x \Phi_{DC}(d/2, 0, z_{ion}) &= a \\ \partial \partial_x \Phi_{DC}(-d/2, 0, z_{ion}) &= a \end{cases} \quad (2.3)$$



(a) 1 MHz trap



(b) 3 MHz trap

Figure 2.9: Voltage required on DC electrodes to trap two positive ions at a distance of 10 μm and 20 μm , respectively for 3 MHz and 1 MHz, trap in function to the electrode width.

2.2.3 Voltage and design comparison

The table 2.2 summarize the geometrical and voltage parameters in the four cases in consideration. It results that these configurations are nearly impossible to do in practice with the Positive-Positive planar trap as VDC_2 is very high. As conclusion of this part, Negative-Positive ion traps would allows more convenient configuration in term of heating rate and ion coupling.

Trap Technology	Trap frequency	Distance between ions	Electrode width	VDC ₁	VDC ₂	VDC ₃
Negative - Positive	1 MHz	20 μm	195 μm	12.9 V	10.6 V	-
	3 MHz	10 μm	98.5 μm	29.8 V	24.4 V	-
Positive - Positive	1 MHz	20 μm	130 μm	0 V	391 V	82.7 V
	3 MHz	10 μm	65.5 μm	0 V	911.9 V	195.2 V

Table 2.2: DC electrodes voltage and geometry.

2.3 Trapping potential with Coulomb interaction

The final step of this simulation is to plot the potential to find the ions positions and their modes of oscillation considering coulomb interaction. The ions equilibrium position corresponds to the minimum of the total electric potential which is defined as the sum of the static potential generated by DC electrodes and the Coulomb potential.

In this section, the oscillation modes of the ions pair and their corresponding frequencies are also calculated. This is done by considering the Hessian matrix of a one dimensional the system. Indeed, working around an equilibrium point mean that the first derivative of the potential must be zero. This leads to approximate the potential as harmonic close to the equilibrium. Using Taylor expansion:

$$V(\mathbf{q}) \simeq V(\bar{\mathbf{q}}) + \frac{1}{2} \sum_{i,j} \partial_{q_i} \partial_{q_j} V(q_i - \bar{q}_i)(q_j - \bar{q}_j) \quad (2.4)$$

In this expression, $\mathbf{q} = (q_1, q_2)^T$ and correspond to the position of the first (q_1) and second (q_2) ion, V is the total potential and $\bar{\mathbf{q}}$ correspond to the equilibrium position.

Defining a vector $\mathbf{x} = (x_1, x_2)^T$ with $x_i = q_i - \bar{q}_i$ describes the distance of the i^{th} ion from its equilibrium. We can rewrite (2.4) in a matrix form:

$$V(\mathbf{q}) \simeq V_0 + \mathbf{x}^T \mathcal{H} \mathbf{x} \quad (2.5)$$

With $\mathcal{H}$ the Hessian matrix in 1D defined as:

$$\mathcal{H} = \begin{pmatrix} \frac{\partial^2 V}{\partial x_1^2} & \frac{\partial^2 V}{\partial x_1 \partial x_2} \\ \frac{\partial^2 V}{\partial x_2 \partial x_1} & \frac{\partial^2 V}{\partial x_2^2} \end{pmatrix} \quad (2.6)$$

Reminding that the total kinetic energy of the ions is given in general for a multi particle system by:

$$T = \frac{1}{2} \sum_{i,j} m_{ij} \dot{x}_i \dot{x}_j \quad (2.7)$$

Please notice that in our case $m_{ij} = m_i \delta_{ij}$. Considering the Lagrangian $L = T - V$ and solving equation of motion with complex solutions in the form $\mathbf{z} = \mathbf{A}e^{i\omega t}$, we obtain:

$$\mathcal{H}\mathbf{A} = \omega^2 M\mathbf{A} \quad (2.8)$$

Where M is a mass matrix with $M_{ij} = m_{ij}$. In our case, considering particles of equal mass m , we have $M = mI_d$. In this situation, the equation (2.8) search for $\mathbf{A}$ eigenvector of the Hessian matrix and $\lambda_i = m\omega_i^2$ its eigenvalues. This is meaningful since the two eigenvectors will correspond to oscillations modes with a resonance frequency of $\omega_i = \sqrt{\lambda_i}/m$. The results of this calculation are shown in tables 2.3 to 2.6 where e_x correspond to the normalized eigenvector coordinate for each ions. If the e_x values for both ion have the same sign it correspond to in-phase oscillations. If the sign is different, it corresponds to counter-phase oscillations. An interesting point to notice in the following results is that the lowest frequency mode for negative-positive ion traps is counter-phased, whereas for positive-positive ion traps the lowest frequency corresponds to in-phase oscillations.

2.3.1 1 MHz Trap

In the case of 1 MHz trap, the electrode potential was designed to have the ions at a distance of 20 μm . Adding the coulomb interaction gives the following results:

- Negative-Positive ion trap: $d = 17.14 \mu\text{m}$, relative error: $e = 14.3 \%$
- Positive-Positive ion trap: $d = 21.51 \mu\text{m}$, relative error: $e = -7.5 \%$

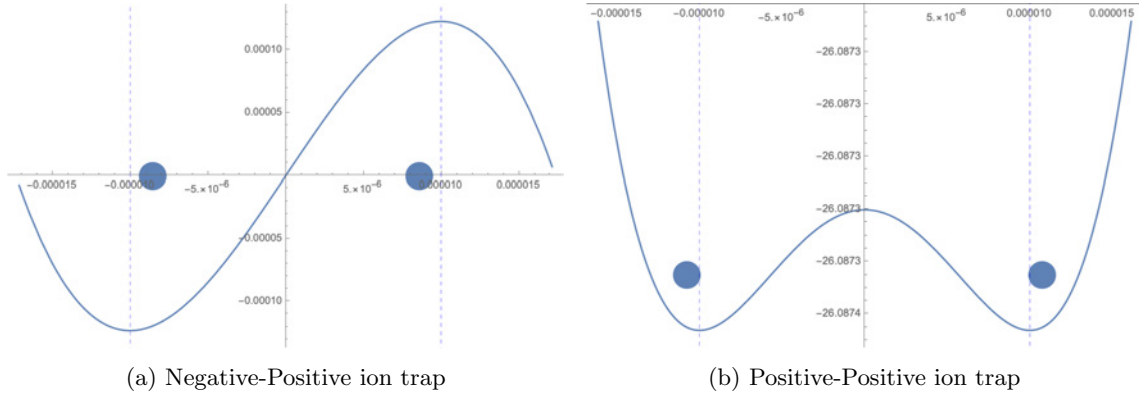


Figure 2.10: Ions position in the longitudinal potential of each trap technology considering coulomb interaction. Trap frequency of 1 MHz with DC local potential extrema at a distance of 20 μm .

Negative-Positive Ion trap

Mode Frequency	ion charge/mass:1/9.01493	ion charge/mass:-1/9.01493
	e_x	e_x
0.925868	0.707	0.707
0.73943	-0.707	0.707

Table 2.3: Oscillation modes for 1 MHz, Negative-Positive Ion trap

Positive-Positive Ion trap

Mode Frequency	ion charge/mass:1/9.01493	ion charge/mass:1/9.01493
	e_x	e_x
1.17948	-0.707	0.707
1.11096	-0.707	-0.707

Table 2.4: Oscillation modes for 1 MHz, Positive-Positive Ion trap

2.3.2 3 MHz Trap

In the case of 3 MHz trap, the electrode potential was designed to have the ions at a distance of $10\text{ }\mu\text{m}$. Adding the coulomb interaction gives the following results:

- Negative-Positive ion trap: $d = 8.81\text{ }\mu\text{m}$, relative error: $e = 11.9\%$
- Positive-Positive ion trap: $d = 10.69\text{ }\mu\text{m}$, relative error: $e = -6.9\%$

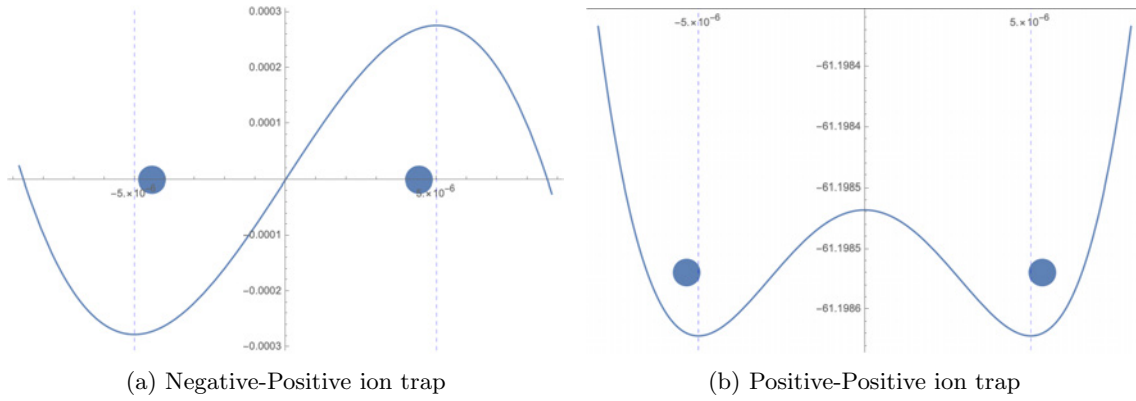


Figure 2.11: Ions position in the longitudinal potential of each trap technology considering coulomb interaction. Trap frequency of 3 MHz with DC local potential extrema at a distance of $10\text{ }\mu\text{m}$.

Negative-Positive Ion trap

Mode Frequency	ion charge/mass:1/9.01493	ion charge/mass:-1/9.01493
	e_x	e_x
2.81679	-0.707	-0.707
2.37728	0.707	-0.707

Table 2.5: Oscillation modes for 3 MHz, Negative-Positive Ion trap

Positive-Positive Ion trap

Mode Frequency	ion charge/mass:1/9.01493	ion charge/mass:1/9.01493
	e_x	e_x
3.49079	-0.707	0.707
3.30237	-0.707	-0.707

Table 2.6: Oscillation modes for 3 MHz, Positive-Positive Ion trap

2.4 Next improvements for better simulation accuracy

To improve the accuracy of this planar trap simulation, the DC electrodes contribution at the chosen z-position has to be taken into account. This contribution don't exist for 3D Paul traps like the one fabricated during this project. Indeed, the point symmetry of a quadrupole trap design, like the one represented in Figure 1.1, necessarily have a null DC electric field at the its center. For a planar trap, this assumption cannot be done since DC electrodes will create non-null electric field along z-axis with different contribution if the voltage is positive or negative.

This electric field can be easily corrected by the central electrode in the case of a positive-positive ion trap but required more design constraints in negative-positive case. Indeed, the field component in this situation will be alternatively positive and negative which cannot be compensated only by the central electrode voltage. In general, these considerations will add a couple electrodes more on the sides of the trap, with the constraint of null electric field at the ion position.

Chapter 3

Experimental Setup

In this chapter, we will focus on the modeling of the experiment. Starting from a description of the monolithic trap we would like to manufacture, we will then discuss its implementation in a vacuum chamber and the different devices required for the realization of the experiment. Finally, ultra-high vacuum constraints will be detailed as well as the conception of a dedicated printed circuit board (PCB) to control the trap electrodes.

3.1 Trap design

The design of the trap has been created during summer 2020 by Dr. Ilia Sergachev. Thanks to Ilia's work, I was able to focus on the fabrication.

The 3D model of the trap is shown in figure 3.1. The main cavity is the one at the top of the trap. It corresponds to the place where the ions will be trapped. It is accessible from both faces and from the top of the trap. This allows to coat the electrodes by gold evaporation and to easily interact with the trapped ions. Several features are also present in this design. The circular holes on the right and left sides of the trap are openings to access the main cavity from the sides. This can be used for several purposes as ionising atoms (e-gun), cooling, encoding quantum information (lasers) or loading ions. In this setup, the right hole will be used to load the deuterium anions. Indeed, these negatively charged ions will arrive in the chamber with high energy. They therefore have to be stopped with the DC potential of the electrodes before being trapped. Additional channels can be used to e.g send a neutral atom beam into the trap are at a 45° angle. The end in the rectangular openings at the side face of the structure is visible in the drawing. In the final chamber design (Fig. 3.3), the left one is used to load beryllium atoms into the cavity from the oven. The bottom cavity in the trap allows the electrodes to continue on both recto-verso faces of the traps. This is important in a Paul trap because the electrodes

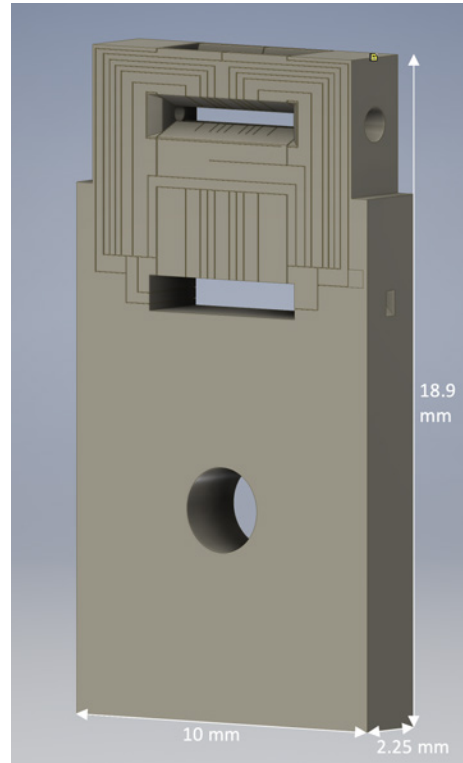


Figure 3.1: Trap CAD design - Autodesk Inventor 2019.

have to be symmetric two by two (section 1.1.2) and it allows us to make all the bonds on the same side. Finally, the central circular hole in this trap design allows to screw it on a dedicated mount (section 3.3.3). The trap consist in a monolithic bloc with 24 direct current (DC) and 3 Radio-Frequency (RF) electrodes. Using the naming of the figure A.1 in appendix, the purpose of the electrodes are:

- **Electrodes 1, 6, 8 and 23:** These are compensation electrodes used to correct the DC potential by defining the main oscillations axis for the trap.
- **Electrodes 2 to 22:** For the longitudinal trapping of the ions. Using an appropriate sequence allows to load the ions inside this trap and to bring them close to each other for the coupling.
- **Electrode 24:** Correspond to the housing of the trap. This area will be covered by gold like the other electrodes and must be connected to ground to not have a floating potential.
- **RF 1:** This is a loop electrode. It can be used for the generation of oscillating magnetic fields in the trap.
- **RF 2 to 3:** These are the electrodes which create the pseudo potential with a radio-frequency field as explained in the first chapter (Fig. 1.1).

The tracks and the electrodes are separated from each other with T-shape features in the substrate bulk (Fig. 3.2). The idea behind this shape is to avoid electrical connections between them, without using a mask during the evaporation process. Indeed, gold coating by evaporation consist in a very directional process as explained in section 4.5. The gold particles follow a linear trajectory and should not be able to ‘come back’ and coat the hidden area of the T-shape. The main advantage of this design is to decrease the number of steps needed for the fabrication and therefore to improve the reproducibility of the process. Trenches also allow to insulate electrodes in such complex 3D structures which could be very challenging using shadow masks.

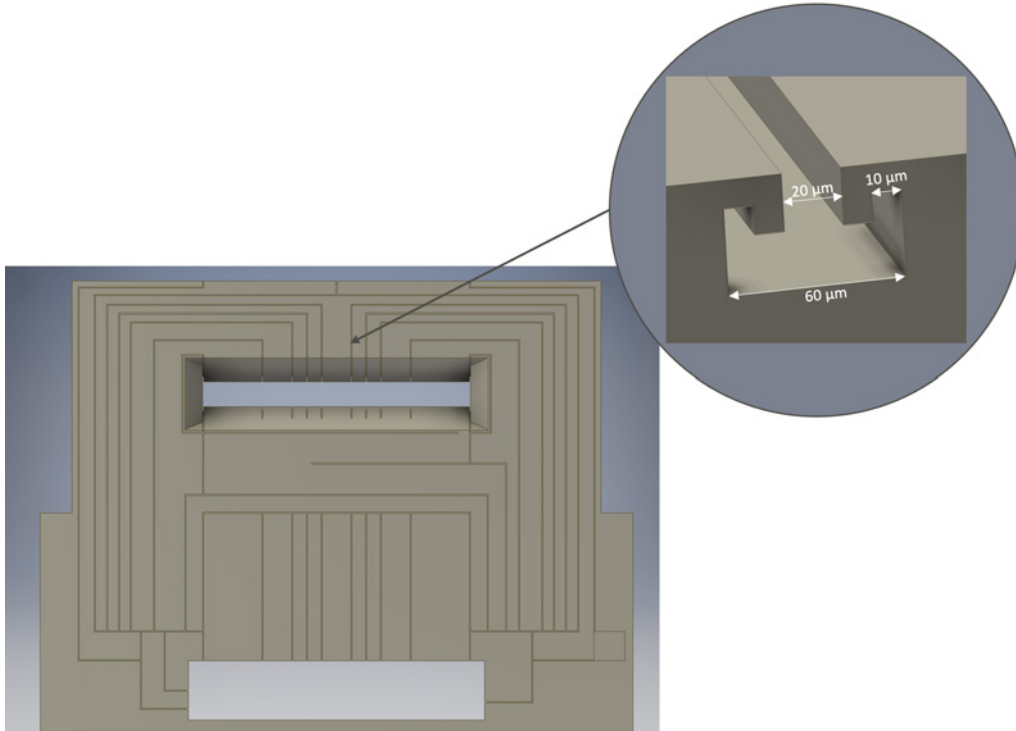


Figure 3.2: Trap CAD design - Autodesk Inventor 2019. Details of the T-shape using half-view.

3.2 Experiment description and ultra-high vacuum constraints

Experiments with trapped ions currently take place in ultra-high vacuum (UHV). This correspond to a chamber pressure below 1×10^{-9} mbar. In our case, the pressure is expected to be in the 1×10^{-11} mbar range, like the other experiments conducted in TIQI group. To achieve this pressure range, a scroll pump makes the chamber pressure drop until 1×10^{-1} mbar and a turbo molecular pump is started afterward to set the chamber in ultra-high vacuum. However, to be able to drop the vacuum to 1×10^{-11} mbar, several considerations have to be made. Indeed, at this pressure range the limitation comes from gas molecules absorbed to the chamber walls and small cavities which can trap air, so-called ‘virtual leaks’ - for example at the tip of a screw in a hole. These limiting factors cause slow gas release in the chamber which prevent UHV pressure to be achieved.

To compensate these effects, the goal is to choose adequate materials, which are not easily contaminated and have very few molecule evaporation under vacuum. We can also notice that precautions are required even with suitable materials, which consist in cleaning all the parts with Acetone-IPA-Water protocol (Section 4.3.1) and wearing latex dust-free gloves when assembling the chamber. Once the chamber assembled, a baking must be performed. In addition, parts have to be designed to avoid air trapping.

Baking of the chamber

Baking out the chamber has the main effect to pump out the residues present in it, more specifically water and hydrogen. The process consist in heating the chamber, in this case, close to 200 °C while pumping with roughing and turbo molecular pump. To proceed, the chamber is placed in an oven while the pumps are connected from outside with tubes. The total procedure takes around two weeks.

Ultra-High vacuum parts

To avoid air trapping in our chamber, vented screws must be used to fixed the parts. The company VACOM¹ provide UHV screws which have the particularity to be drilled from their tip to their cap. This feature allows air to flow outside the screw and avoid air cavity. According to the same principle, all the fixations plates had been designed to not cover the unused holes of the support. We can well see on all the plates drawing (appendix D) that the face in contact with the chamber is not flat. Indeed, it is made such that only the areas screwed to the chamber will be in direct contact with it. The other zones are slightly elevated to create access for the air to flow out.

¹<https://www.vacom.de/en/products/vacuum-suitable-screws>

3.3 Mechanical parts

To achieve the trapping of negative and positive ions, an experimental setup needs to be constructed. It consists of mounting the trap inside a vacuum chamber with an electron gun, an oven and a dedicated PCB to control the trap electrodes. The global design of the experiment chamber is exposed in figure 3.3. All these components have been designed in Autodesk Inventor 2019 and the complete set of formal drawings can be found in appendix D. The main constraint was to design parts to generate and load beryllium cations (Be^+) while positioning the trap in a way that all the beams can access the cavity (lasers and deuterium anions beam).

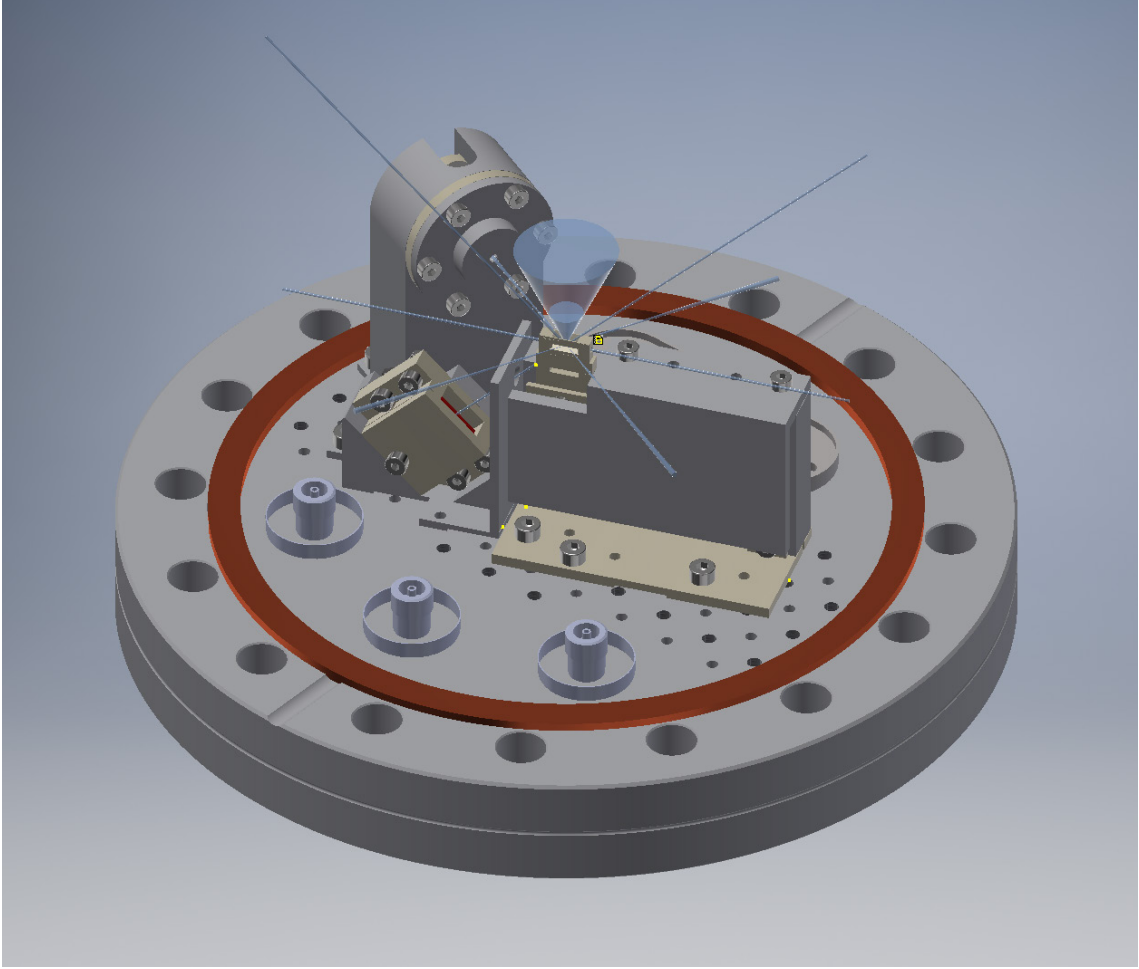


Figure 3.3: Vacuum chamber CAD design overview.

3.3.1 Electron gun

The purpose of the electron gun is to ionize the beryllium atoms emitted by the oven. That means high energy electrons are required and, to reach this energy, we accelerate them at the output of the e-gun. This is done by applying negative bias on the aluminium part around the e-gun. The electrical access to the e-gun housing is done by the top screw. To insulate it from the chamber which is grounded, yellow parts are fabricated in Macor (easily machinable ceramic material). All the other aluminium parts are connected to the chamber ground.

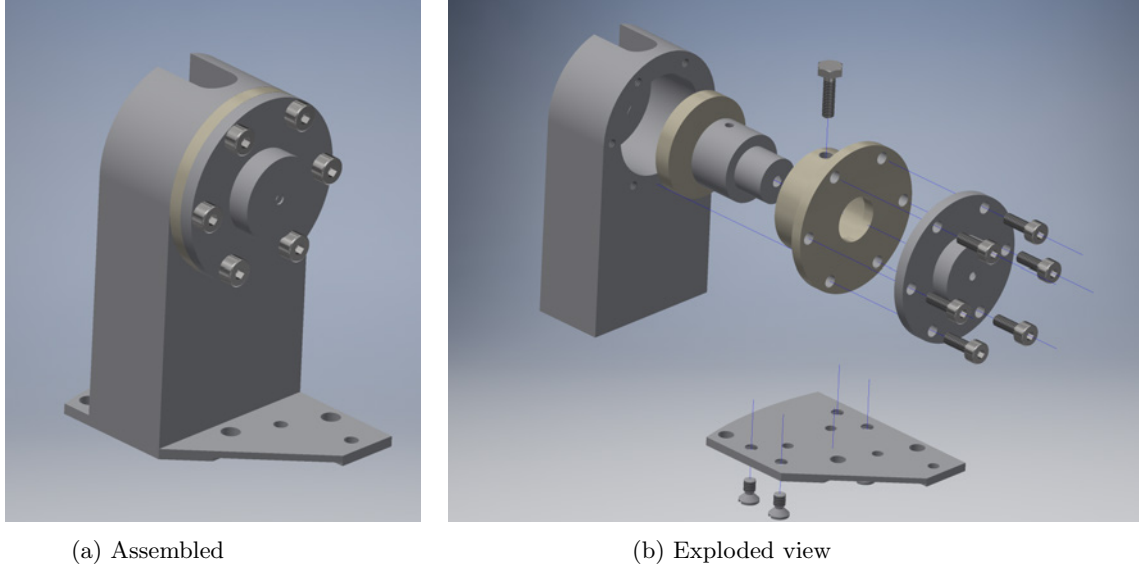


Figure 3.4: Electron gun CAD design.

3.3.2 Oven

The oven is the part of the chamber used to emit beryllium atoms. This is achieved by heating a tungsten wire with a beryllium filament wrapped around it. The tungsten wire is heated with Joule effect by flowing an electrical current through it. Red cylinders in figure 3.5 correspond to a tungsten wire with a beryllium filament around. This system is installed two times in the oven to have a spare filament ready if the first one breaks. On the right of the assembly, an aluminium shield is installed. Its purpose is to reduce beryllium deposition and heat transfer to the trap (Fig. 3.3). Indeed, the beryllium atoms are thermally emitted and are therefore flowing in all direction in the chamber.

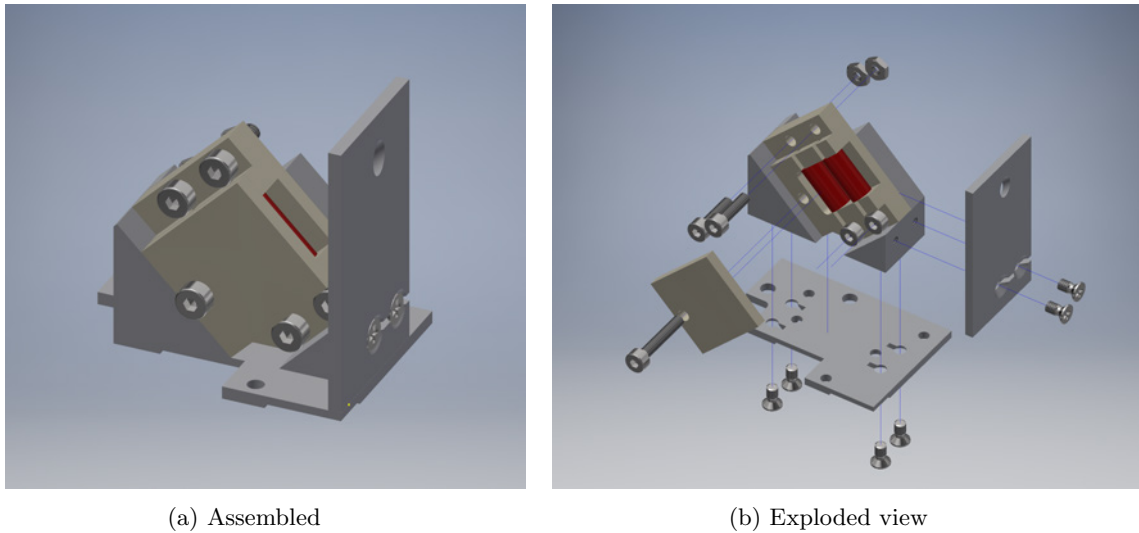


Figure 3.5: Oven CAD design.

3.3.3 Trap Holder

This assembly correspond to parts which hold the trap in the chamber. A PCB is assembled and wire bonded to the trap electrodes. The yellow parts (except the trap) are made from PEEK (PolyEtherEtherKetone) to isolate the ground of the trap from the chamber ground. Furthermore a Kapton foil is placed between the trap and the PCB to avoid electrical shorts. The PCB has to be ultra-high vacuum compatible and, in this context, there is no plastic layer protecting the electrical tracks. It means that tracks of the bottom layer would touch and connect to the aluminium part if no insulating plate is placed in-between.

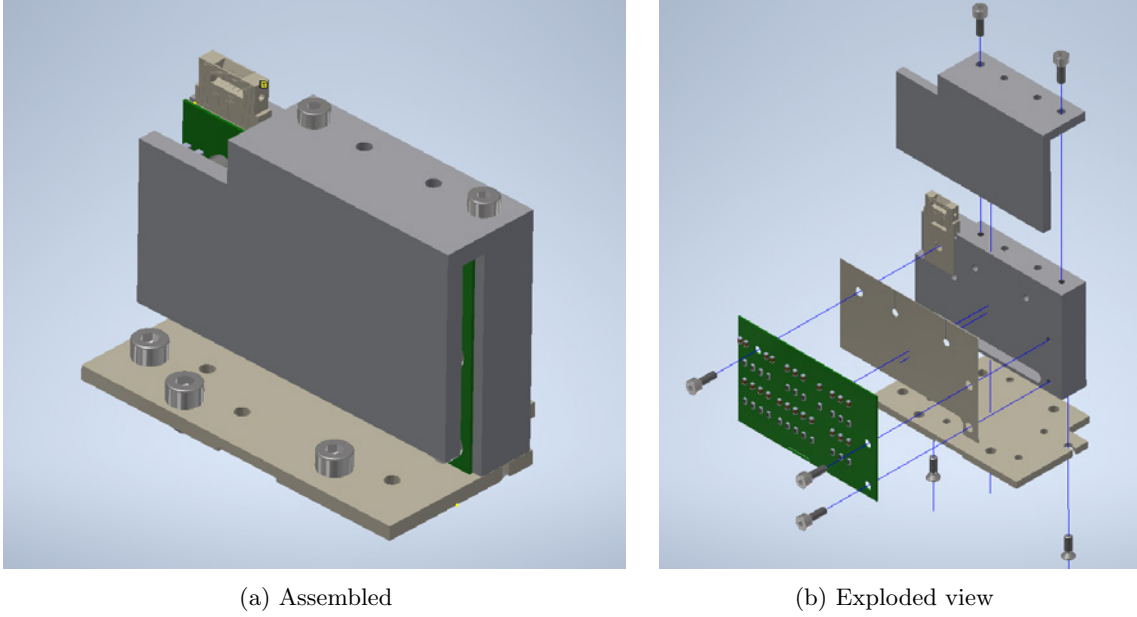


Figure 3.6: Trap holder CAD design.

3.4 PCB design

The PCB layout is shown in figure 3.7. There are four layers in this picture, the blue corresponds to the tracks in the back of the PCB. We find on this bottom layer the RF tracks and the ground polygon that almost covers all the layer area. The red features correspond to the tracks on the top conductive layer, where the footprint of all the components are positioned as well as the electrical paths between them. Finally, the black area corresponds to the dielectric layer between the top and bottom conductive features. Contrarily to common case, this PCB only has the three layers described just before. It means that the tracks, on both faces, are not protected and exposed to air. This must be done this way because of the ultra-high vacuum of the chamber. In these circumstances, the yellow drawings, which are currently printed on the plastic protective layer, exist only in the software.

The goal of this PCB is to reduce the high frequency power supply noise on the DC electrodes with low-pass filters. Indeed, electronic noise acts directly on the confining potential and will cause the ion motion to heat up, which affects the quantum logic operations. The filter also serves the purpose to provide a ground for the RF potential. Due to space constraint, a complex low-pass filter cannot be implemented for each DC electrode. Simple RC circuits have therefore been implemented on this PCB. The components are chosen to have lead-free termination to be UHV compatible. The components have a 0603 footprint which corresponds in SI units to component

of 1.55 mm x 0.85 mm size. This allows to fit them all in a board of 46 mm x 30 mm. A set of 820 pF capacitors² was already available in the laboratory and resistors of 250 Ω ³ had been ordered for this project. The PCB material are also chosen to have high performance in vacuum. The dielectric layer is done in ‘Rogers 4350’ material, which will limit the radio-frequency losses. The pads have ENEPIG (Electroless Nickel Electroless Palladium Immersion Gold) treatment for UHV compatibility and easy bonding. Finally the solder (315-LF-Solder) comes from the company Allectra⁴ which is specialized in vacuum components. The cut-off frequency can be calculated:

$$f_{cut} = \frac{1}{2\pi RC} = 0.776 \text{ MHz} \quad (3.1)$$

The dominant noise of the DC power supply can be assumed to be 1/f. The filter value thus represents the absolute minimum of required filtering because the motional frequencies of the ions are 1 MHz and higher. This frequency would therefore allow fast voltage switching on the DC electrodes while removing the background noise. A battery could also be a relevant choice to have very stable voltages. Indeed, due the chemical nature of the power produced, it produces less noise than a power supply which is base on electronic treatments. However, to well control the voltage from a battery it requires to have special equipment which increase the complexity of the operation on the trap and capacitors would still be required to create the RF ground.

Since this PCB is dedicated to the trap presented in section 3.1, the goal was also to make our life simpler considering the wire bonding step. This technique will be detailed in section 4.7 and basically consist in linking the electrodes of the trap to the PCB pads with micrometer large gold wires. This is a critical step since it can damage the trap coating as well as the PCB pads. In this PCB design, the pads visible on the top left of figure 3.7 has been positioned to be aligned with the trap electrodes.

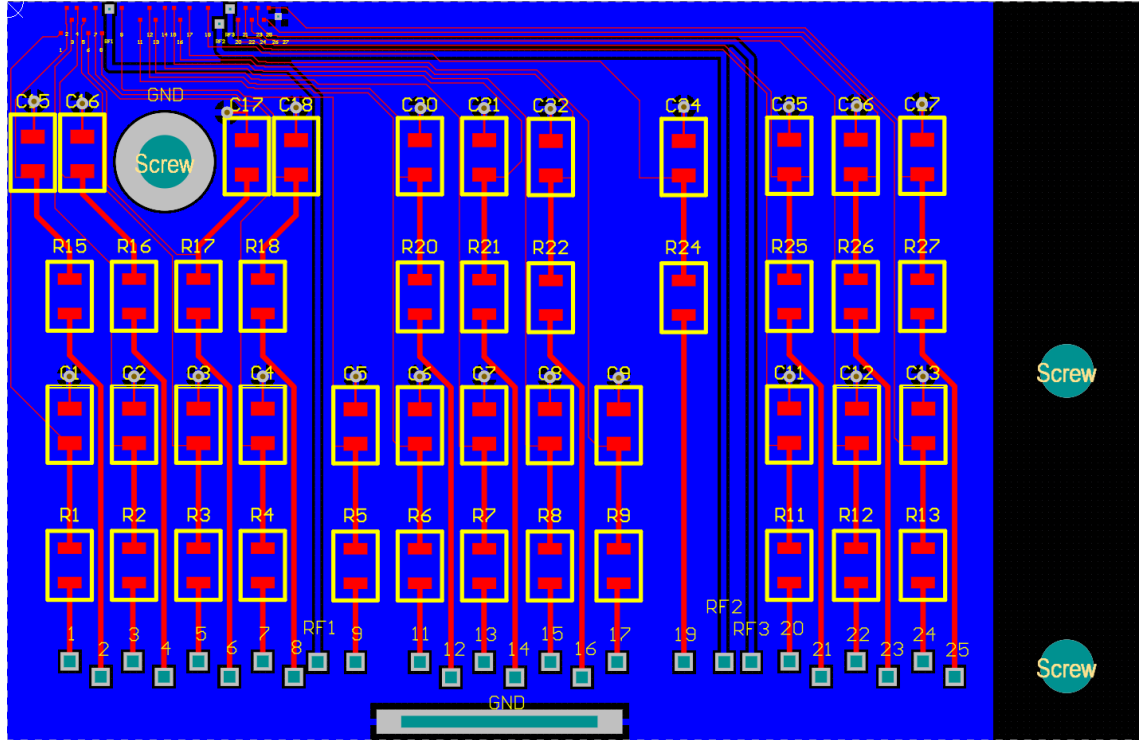


Figure 3.7: PCB layout - designed with Altium designer 18.1.6.

²Knowles capacitors part number: 0603N821J101PRT

³Digikey part number: RT0603BRE07250RL

⁴<https://www.allectra.com/>

Chapter 4

Trap fabrication

In this chapter, we will detailed the cleanroom fabrication steps which lead to a functional monolithic ion trap. Staring from a description of the whole process flow, we will then detail cleaning, etching, coating and wire bonding techniques which were performed during this project. Finally, we will spot fabrication issues which occurred during this project and give some outlooks by introducing alternative methods.

4.1 Process flow

In order to have a good overview of the fabrication, figure 4.1 explains the process flow. This project started after the trap was designed (gray dashed line). The graphic has to be read from the top to the bottom following the connections lines in the direction of the arrows. Each rectangular box corresponds to a step of the global process, while boxes with diamond shape correspond to conditions on the previous step results. Methodically following this graphic would allow anyone to reproduce the same fabrication results for this particular trap. The next sections of this chapter goes into the details of each step.

The fabrication was processed in **FIRST** (Frontiers in Research: Space and Time) center of Micro- and Nanoscience located in ETH H nggerberg campus. The following research equipment has been used:

- **Wet bench:** standard Acetone-IPA-Water cleaning, piranha cleaning, titanium and gold etching.
- **Nikon Eclipse L200 optical microscope:** optical imaging.
- **Zeiss ULTRA 55 plus:** scanning electron microscopy.
- **Plassys II:** e-beam evaporation coating.
- **Karl S ss Prober PM8:** electrical probing of the trap electrodes.
- **Dektak surface step profiler:** profilometry of the gold thickness.
- **UVOCS Cleaner:** UV-ozone cleaning
- **Westbond 747677E:** gold wire bonding.

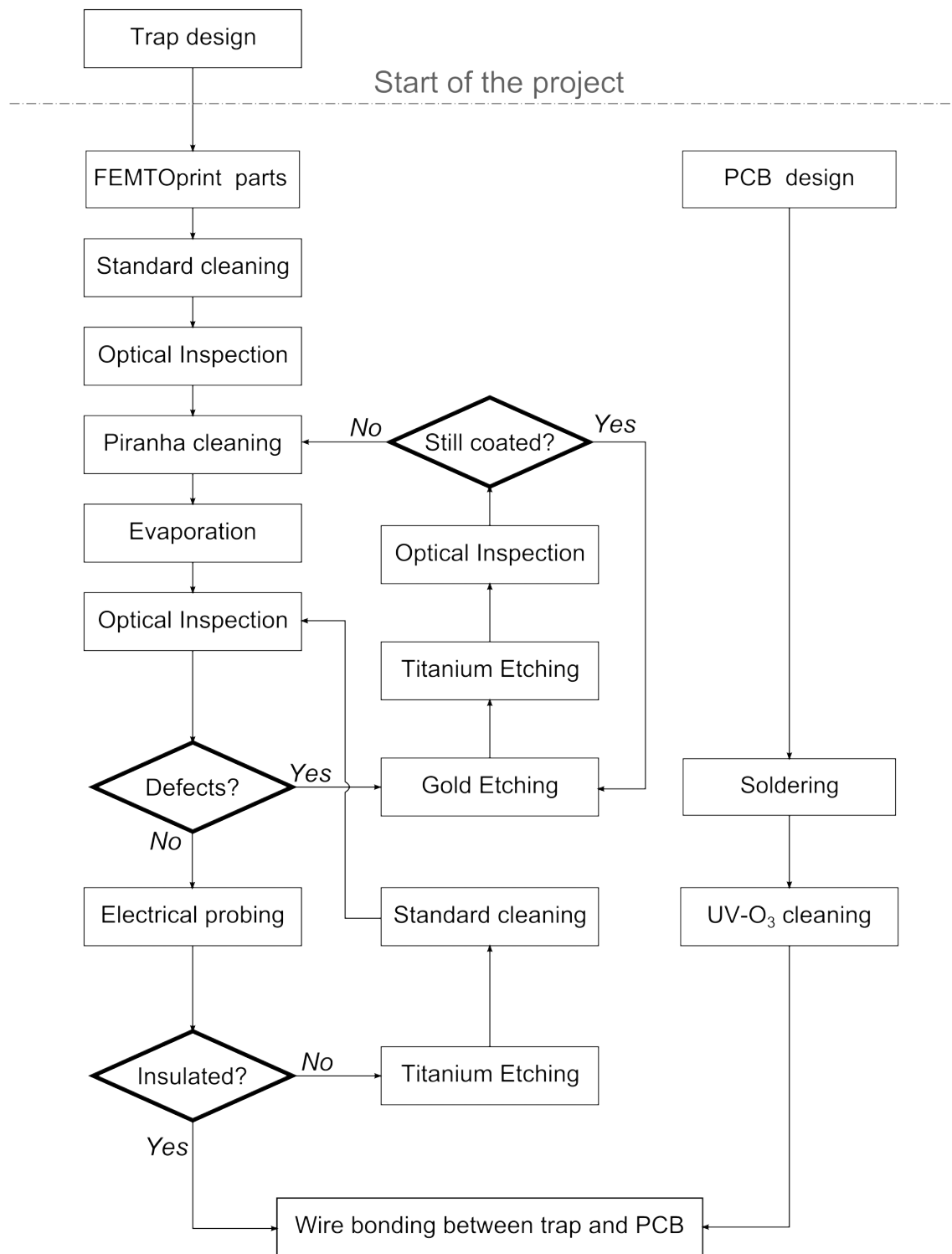


Figure 4.1: Process flow for monolithic traps fabrication.

4.2 FEMTOprint parts inspection

The traps' bulks have been fabricated by the company **FEMTOprint**¹. FEMTOprint is a Swiss company specialized in fabrication of 3D micro-devices. Their fabrication technique consist in glass bulk micro-machining by laser focusing and Hydrofluoric acid (HF) bath. In few words, a laser induced micro-cracks in the glass at its focus point and decreased the density of the material. Once placed in HF, the etching rate is much higher in zones of low material density and this allows to have complex structures at micrometer scale.

For optical inspection a Normarski filter has been used on the microscope. This is specially useful to see defects on transparent samples as it convert surface relief into contrast. It works using two polarizing filters and a prism. The result of this technique is exposed in Appendix C.1.2.

The first step of this trap fabrication is to inspect the FEMTOprint parts. Four identical parts had been ordered. In this chapter, the traps are numerated from 1 to 4 to be easily identified. The first inspection consist in an optical checking of each trap. The complete set of pictures from optical inspection are in Appendix C.1. Another point to check is the shape of the trenches (Fig. 4.5) and the features inside the glass bulk (Fig. 4.3). While focusing at the bottom of the trenches, as done for the right picture in figure 4.5, we can see a scalloping created by the laser steps. Finally the inside channels of the traps are conformed (Fig. 4.3). On the four traps only one critical defect was spotted on the trap nb.1. It is a glass defect on one of the trenches which will indubitably connect the RF1 electrode to the ground (Fig. 4.2).

The last inspection step of the FEMTOPrint parts is to look at the electrodes surface using scanning electron microscopy (SEM). This tool allows to go much higher in magnification and gives three-dimensional pictures of our samples. The results are exposed in figure 4.7. The pictures 4.7a and 4.7b gives a general view of the trap cavity. On pictures 4.7c, 4.7d and 4.7f we can see that the surface of the traps electrodes is rough. After discussing with other TIQI members, this surface roughness is common from FEMTOPrint and would not be problematic for ion trapping. Finally, the surface of the trap is correctly manufactured as shown in picture 4.7e.

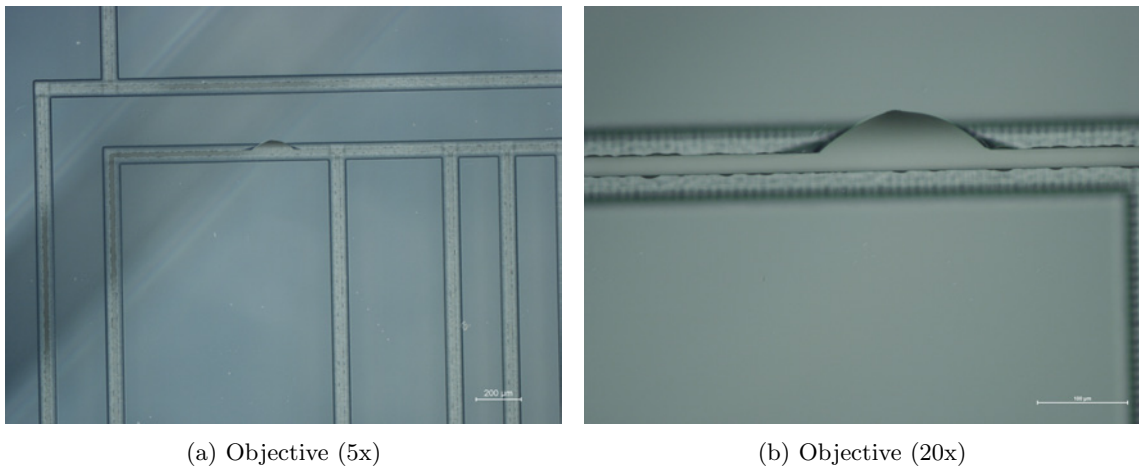


Figure 4.2: Trap nb.1 defect inspection sing optical microscope with Normarski filter. After cleaning with Acetone-IPA-Water standard protocol. This defect correspond to a crack on the trench along RF1 electrode.

¹<https://www.femtoprint.ch>

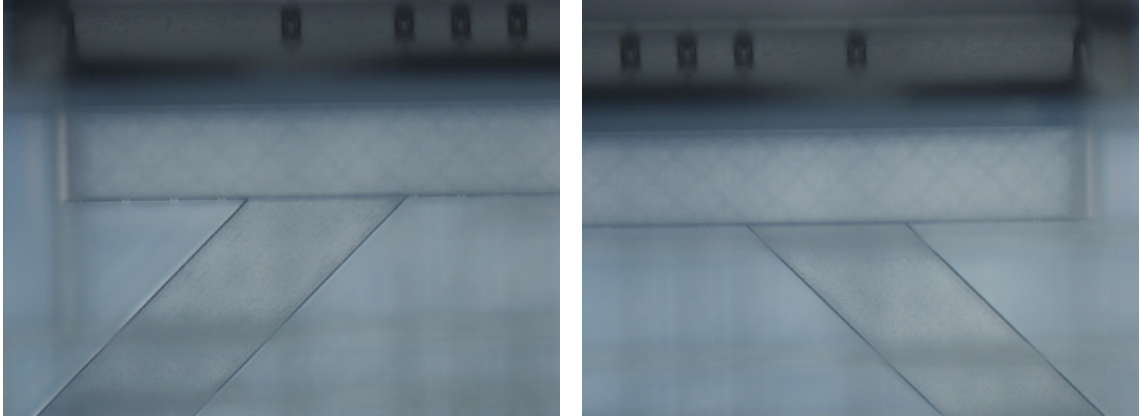


Figure 4.3: Trap Nb.1 inside channels inspection using optical microscope with Normarski filter. Objective 5x.

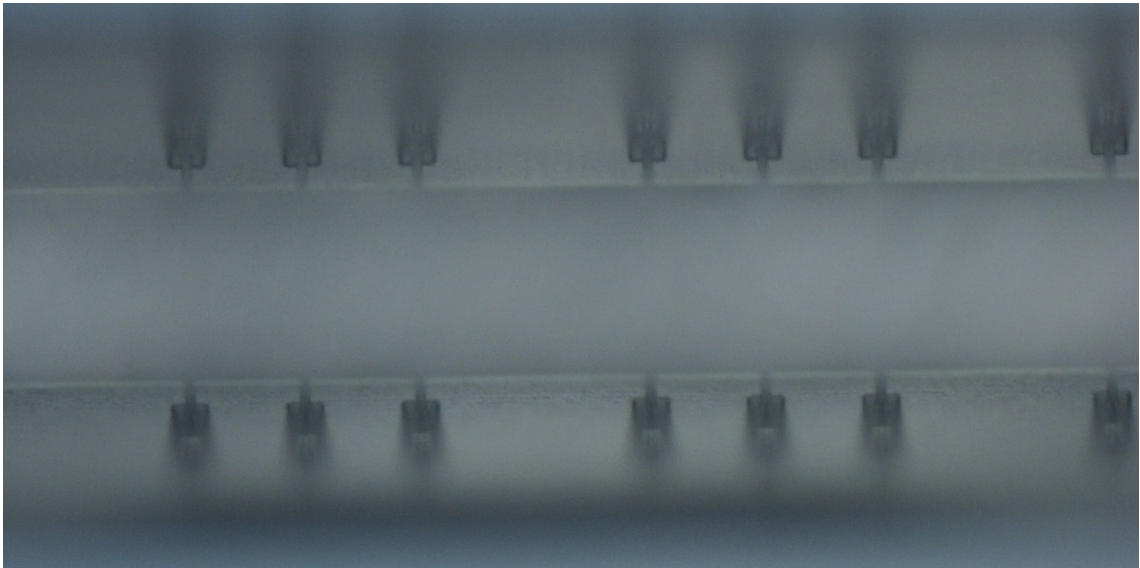


Figure 4.4: Trap Nb.1 electrodes inspection using optical microscope with Normarski filter. Objective 5x.

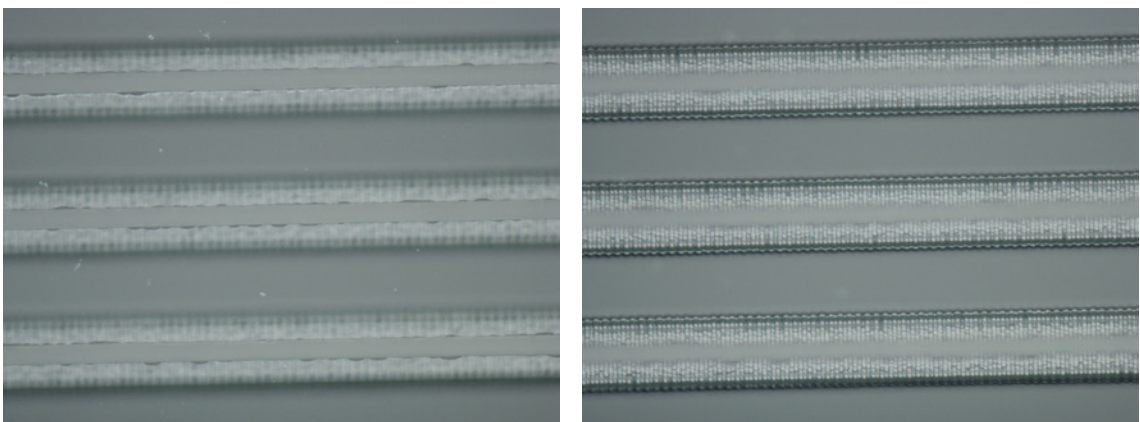
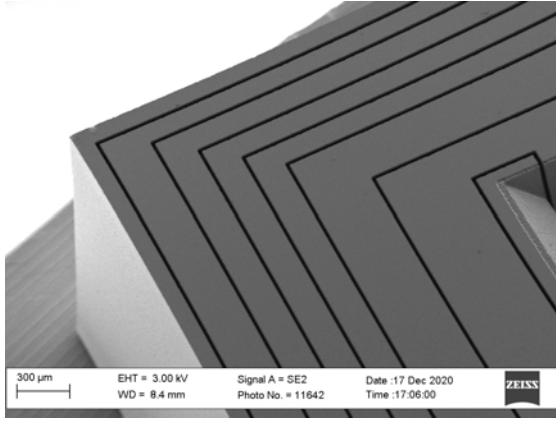


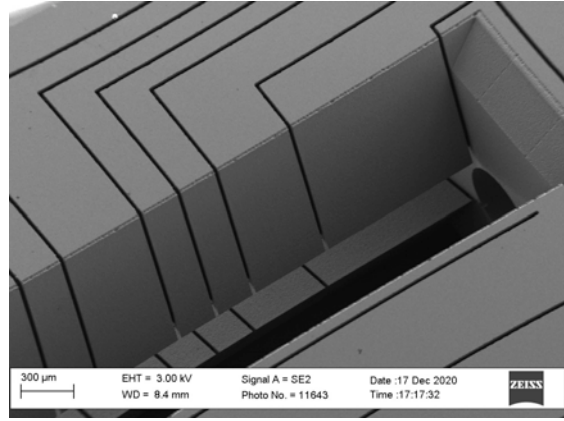
Figure 4.5: Trap Nb.2 trenches inspection using optical microscope with Normarski filter. Pictures taken with two different focal point. Left: focus on the trap surface. Right: focus at the bottom of the trenches. Objective 20x.



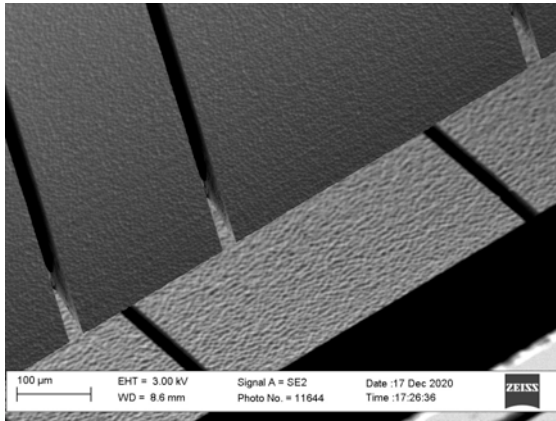
Figure 4.6: Inspection of the top left angle for the four FEMTOprint part. From left to right, top to bottom it corresponds respectively to the traps Nb.1 to 4. These pictures are taken using optical microscope with Normarski filter after cleaning. Objective 5x.



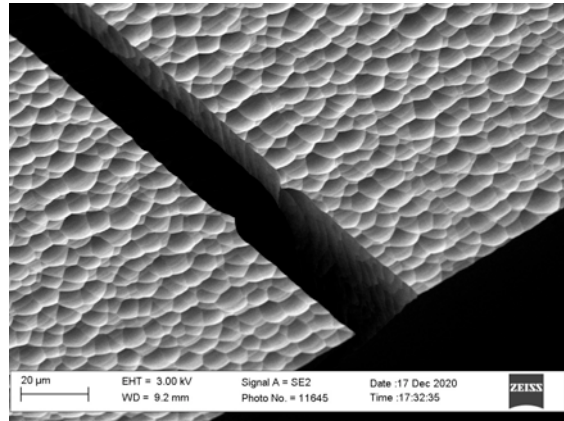
(a)



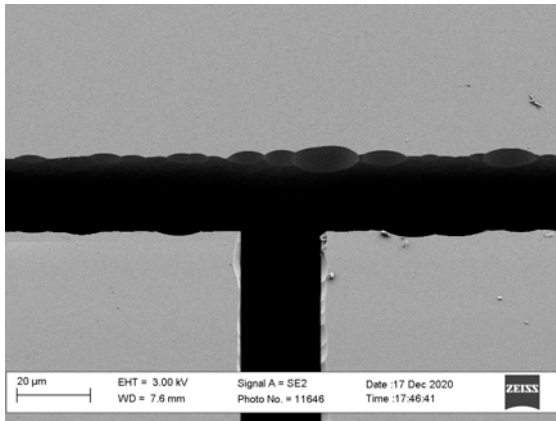
(b)



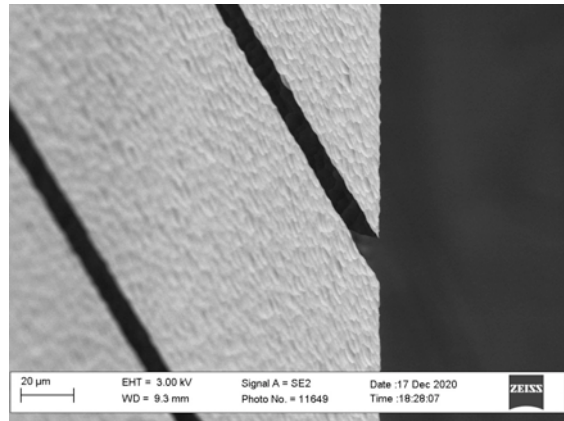
(c)



(d)



(e)



(f)

Figure 4.7: Scanning Electron Microscopy (SEM) pictures of the trap Nb.4 after standard Acetone-IPA-Water cleaning.

4.3 Cleaning

Cleaning protocols are an important part of any fabrication in cleanroom. Indeed, even in a clean environment, processes like evaporation coating are hyper sensitive to contamination. Several protocols exist in function of the context. The more standard one is the Acetone-Isopropanol-Water which must regularly be processed since the samples become dirty over time. This cleaning protocol is also used on parts coming from outside of the cleanroom as first step. Furthermore, UV-Ozone is an adequate cleaning for samples which can be attacked by acetone (plastic material). Finally, the most corrosive cleaning processed during this project is named piranha cleaning. Its name comes from the fact that the acids used etch all organic matters, while keeping intact glass and metal. Piranha cleaning is recommended before any critical steps like evaporation.

4.3.1 Acetone-Isopropanol-Water

The standard cleaning protocol for the trap is composed of three baths. The goal of this procedure is to remove the dirt from our samples with solvent. Following is the protocol:

1. Bath of Acetone at 45-50 °C in the ultrasonic bath for 5 to 10 min.
2. Bath of Isopropanol (IPA) at 45-50 °C in the ultrasonic bath for 5 to 10 min.
3. Bath of deionized (DI) water at 45-50 °C in the ultrasonic bath for 5 to 10 min.

The ultrasonic power of the bath has to be determined taking into account the brittleness of the sample. Indeed, higher power results in cleaner sample but can also damage fragile parts. For example, the aluminium parts used for the evaporation can be cleaned without restriction on the ultrasonic power. However, the FEMTOprint parts are fragile since they are manufactured in glass and have internal stress. In this case no (or low) power was applied and the ultrasonic bath is only used to set a stable temperature.

4.3.2 Piranha cleaning

Piranha solution is used to clean all the organic residues on a sample. This is required before evaporation to have a trap without dirt. It consist in a mixture of concentrated sulphuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2). This solution is working with two process:

1. When the two species are mixed. Rapid dehydration.



2. Generation of reactive oxygen species that can dissolve elemental carbon. Exothermic reaction.



4.3.3 UV-Ozone cleaning

UV-Ozone cleaning is the only dry cleaning process used during this project. There is two main phenomena that clean the sample. The first one consist in decomposition of organic contaminants by ultraviolet irradiation. The substances become volatile and can flow away from the sample. The second process is the strong oxidation by oxygen radicals. These radicals are obtained by the formation and decomposition of ozone (O_3) molecules. This process comes from the interaction

of the di-oxygen (O_2) present in air with the two wavelengths of a low-pressure mercury lamp (184.9 nm and 253.7 nm).

At 184.9 nm we have the ozone formation in two steps.



While the 253.7 nm light decompose the ozone back in oxygen. During these two process a lot of single oxygen radicals O are produced and they create strong oxidation of the organic compounds.

This technique has been used to clean PCB after soldering and the trap before wire bonding to minimise the surface contamination.

4.4 Etching

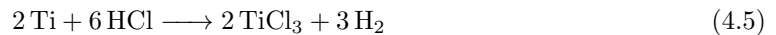
In this project, etching protocols were useful to come back to initial glass substrate, if issues appear during the coating. Wet etching allows to remove titanium and gold layers by using appropriate chemicals. For both gold and titanium etching, different remover solutions exist. Our protocol choice is based on the availability of the chemicals at the cleanroom wet bench and to be inert with the fused silicon trap's bulk (SiO_2). The standard etching rates exposed in this section comes from the publication of Kirt R. Williams [16].

An important point to notice for the etching protocols presented in this section is the presence of Triton-X ($C_8H_{17}C_6H_4(OC_2H_4)_{9-10}OH$). This chemical has the particularity to decrease the surface tension of the acids we used. This allows the etching solution to go in contact with the trap, even inside the trenches that are small features. Only one droplet of Triton-X is added per 10 mL of etching solution.

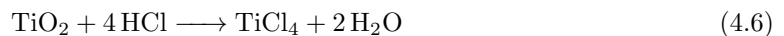
Please notice that the duration exposed in this section for titanium and gold etching are voluntary long to be sure to remove the entire layers. However the duration can be adapted in function of the purpose. This will be illustrated in section 4.6 about electrical probing, a 10 min bath of titanium etching is processed to insulate the electrodes.

4.4.1 Titanium etching

Titanium etching is currently performed with Hydrofluoric acid (HF) in high concentration. This allows an etching rate of 1100 nm/min [16]. However, HF solution are also used for SiO_2 etching and will indubitably damage the trap's bulk. In this context, an alternative solution is to use Hydrochloric acid (HCl), as studied in Kuo-Yung Hung's paper [17]. The reaction is the following:



We can also notice that HCl also dissolve Titanium oxide which could be convenient if our sample is too long exposed to air. Please notice that it should not happen since the titanium layer is covered with gold in the same run of evaporation. The reaction is the following:

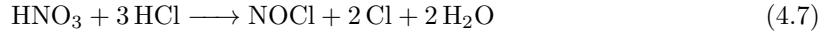


This titanium etching protocol is less aggressive than HF but is appropriated for thin layer like ours (100 nm). Furthermore, according to the same paper [17], the etching rate scale with the temperature from -0.260 mg/min at room temperature to -0.659 mg/min at boiling temperature. A temperature of 50°C is therefore applied, as it is the maximum reachable by the ultrasonic bath of FIRST cleanrooms. For this process, a low ultrasonic power in order to avoid air bubbles in the trap trenches was also applied. The protocol is the following:

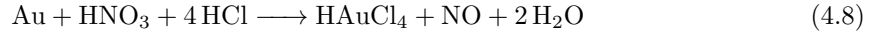
1. Prepare solution with 50 mL of Hydrochloric acid with 5 droplets of Triton-X.
2. Verse the solution on the traps in a beaker. Put the beaker in the ultrasonic bath at 50°C with power at level 2/10 for 30 min. Move the beakers slightly from time to time.
3. Abundantly rinse the trap with DI-water and proceed an Acetone-IPA-water cleaning. Dry the traps with nitrogen gun for several minutes and do an optical check under microscope. If there is still titanium at some places, repeat the whole process.

4.4.2 Gold etching

Gold is a noble metal. It therefore shows a strong resistance to chemical attacks and is very hard to oxidise. An appropriated etching technique is to use a mixture of Nitric acid (HNO_3) and Hydrochloric acid (HCl) in a 1:3 proportion. This solution is usually named ‘aqua regina’ and has a strong enough oxidation power to etch gold. It comes from the formation of nitrosyl chloride (NOCl) once mixed. The chemical reaction occurs in two steps. At first:



In a second step the free chloride radicals Cl react with gold molecules and dissolve them in water to create chloroauric acid (HAuCl_4). The global reaction can be expressed as:



This chemical reaction have an etching rate up to $10\text{ }\mu\text{m/min}$ at room temperature and therefore don’t need to be heated. For the same reason than during titanium etching, a weak ultrasonic power can be applied to avoid air bubble in the trenches. The protocol is the following:

1. Prepare aqua regia solution by versing on the traps in a baker 20 mL of Nitric acid followed by 60 mL of Hydrochloric acid. Finally add 5 or 6 droplets of Triton-X.
2. Put the beaker in the ultrasonic bath at room temperature with power at level 2/10 for 30 min. Move the beakers slightly from time to time.
3. Abundantly rinse the trap with DI-water and eventually perform an Acetone-IPA-water cleaning. Dry the traps with nitrogen gun for several minutes and do an optical check under microscope. If there is gold left at some places, repeat the whole process.

4.5 Evaporation coating

The deposition by material evaporation belongs to Physical Vapor Deposition (PVD) techniques. It consists in heating a crucible with an e-beam or a heater to the evaporation point. The molecules therefore flow from the bottom to the top of the chamber until they deposit onto the substrate. The Plassys II² available in FIRST cleanroom is an e-beam evaporation machine with a rotating planetary system similar to drawing in figure 4.8. It allows to chose a fixed incidence angle for the rotating place where our sample is attached.

Some considerations can be mentioned to better handle this process. High enough vacuum must be set in the chamber in order to avoid collisions between the evaporation flux and air molecules. It means that the mean free path of the molecules has to be in the order of chamber dimension (≈ 1 m). Furthermore, it is a very directional deposition and a ‘shadow effect’ therefore has to be considered. Indeed, all the areas which are not directly exposed to the flux would not be covered by the crucible material. In this project we are making advantage of the shadow effect to insulate our trap electrodes by using T-shapes inside the bulk (Fig. 3.2). The hidden areas inside the glass bulk cannot be exposed to the flux and will therefore avoid electrical connections between electrodes through the trenches (Fig. 4.9).

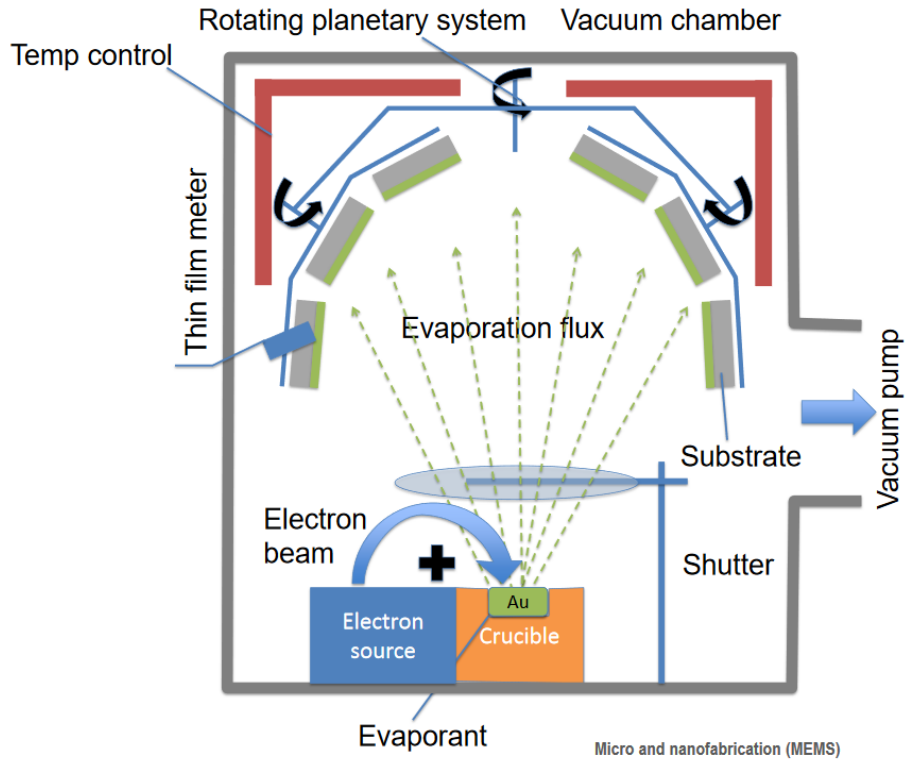


Figure 4.8: Physical Vapor Deposition (PVD) by e-beam evaporation working principle. Image from third year bachelor course in micro-engineering at EPFL: ‘Technologie des microstructures’.

²<https://first.ethz.ch/equipment/first-equipment/pvd.html>

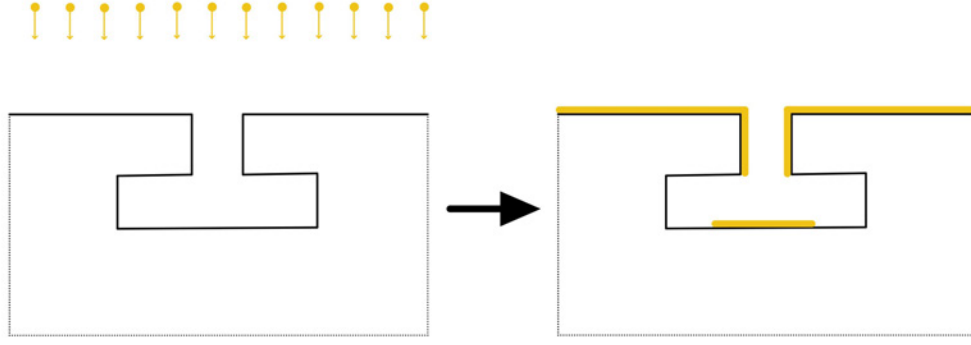


Figure 4.9: T-shape behavior during evaporation coating. The directionality of the flux cannot cover hidden areas and allows to electrically insulate left and right electrodes.

4.5.1 Holder part for evaporation

To perform the gold coating by evaporation, a dedicated holder to mount the trap in the chamber is required. The main difficulty was to design a mount in a way that all surfaces of the trap will be coated in a minimum amount of steps. The planetary system of the chamber must be used in order to overcome the directionality of the process. The final design of the trap holder is shown in figure 4.10 and all the parts dimensions can be found in Appendix D.4.

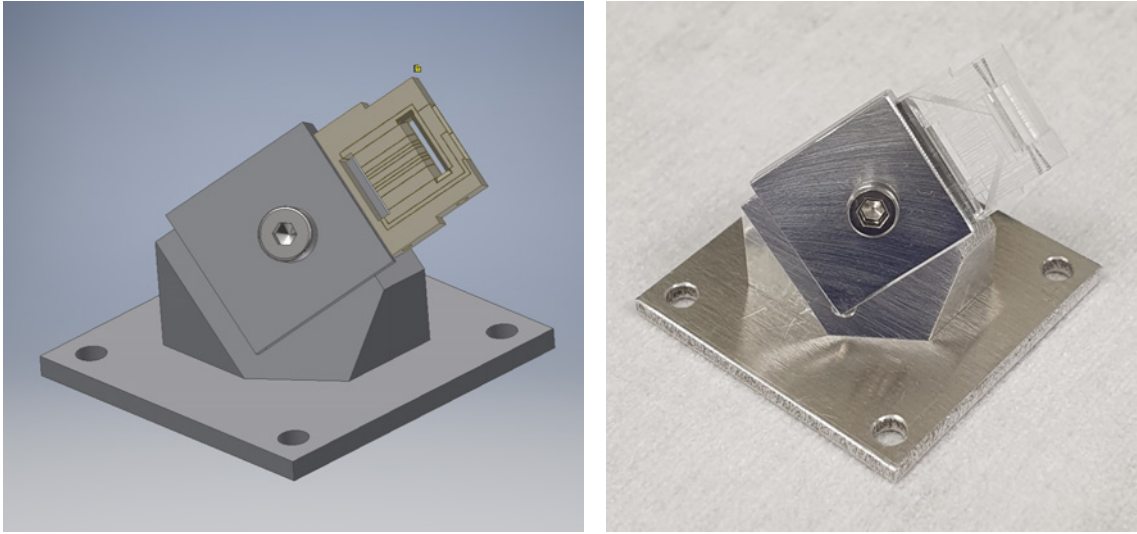


Figure 4.10: Evaporation holder design. (Left) CAD model. (Right) Picture of the holder.

The particular shape of the mount allows a deposition of gold over three faces, if fixed on a rotational plate with an incidence angle of 60° . This has been investigated with the help of Autodesk Inventor software. The degrees of freedom of the evaporation stand had been reproduced and we looked at the mounted trap in the direction of the flux. In figure 4.11, we can see that an angle of 60° allows to expose three faces of the trap during one complete rotation. This trap holder therefore allows a complete coating in two runs of evaporation considering that the trap must be flipped once.

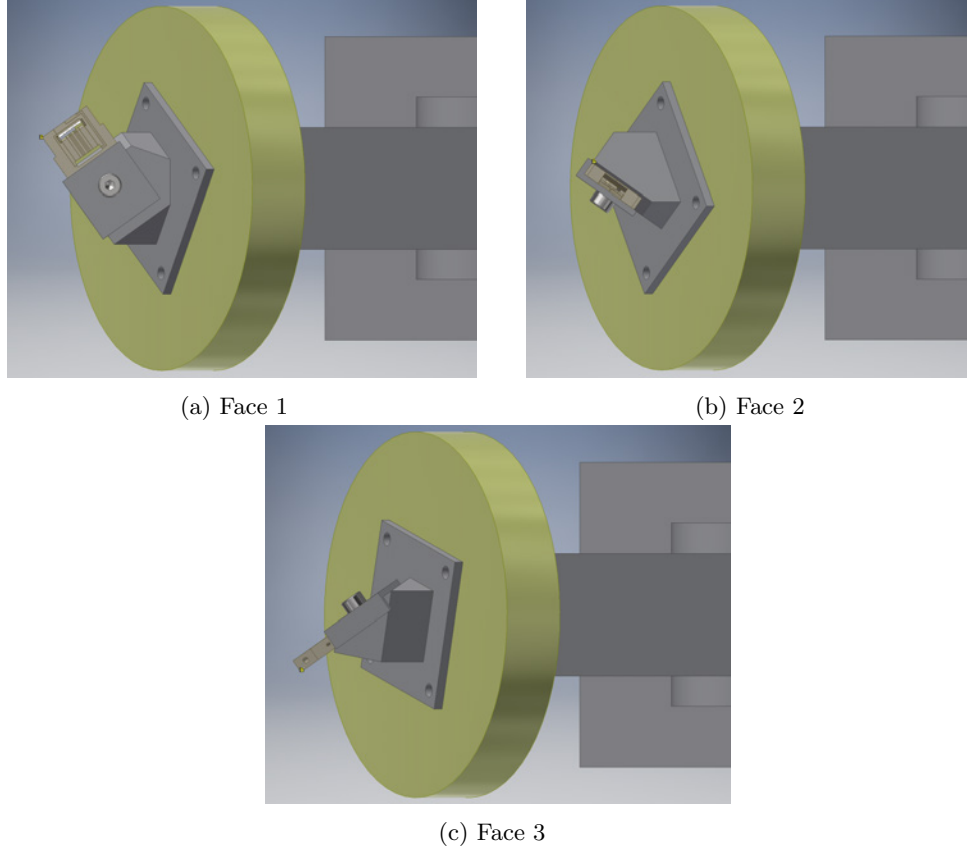


Figure 4.11: Study of the evaporation on planetary system using Autodesk Inventor 2019.

4.5.2 Recipe

Due to FIRST cleanroom rules for evaporation, only layer of maximum 200 nm per material can be deposited on samples. To reduce the difficulties of wire bonding, we would like to have the thickest layer of gold achievable. Furthermore, to have a good adhesion of the gold on our glass sample, a first layer of titanium is required. The detailed recipe is the following:

1. **Chamber pump $1e^{-7}$ mbar:** This step is needed to obtain a directional flux of particles. Indeed, at this pressure the mean free path of the molecules is longer than the height of the chamber.
2. **Start Planetary 4 rpm:** The sample start to rotate. The rotation speed is arbitrary and comes from the recipe of Nick Schwegler.
3. **Ti 0.5nm/s; Thickness 100nm; Tilt 60° :** Titanium coating. The tilt angle is determined from the holder design.
4. **Au 0.5nm/s; Thickness 200nm; Tilt 60° :** Gold coating. The tilt angle is determined from the holder design.
5. **Stop Planetary:** End of the process.

4.5.3 Results

The result of the evaporation on the traps is shown in figure 4.12. At a first inspection, the gold coating seems to completely cover the surface of the trap. The optical inspection of the electrodes confirmed this guess (Fig. 4.14 and 4.13). Please find in appendix C.2 the complete set of pictures to investigate the gold coating. On figure 4.15, pictures of trap nb.1 electrodes was taken by scanning electron microscopy. Since we do not see any marks or brightness differences we concluded that the coating is uniform. We can assume at this stage that the holder was well design and made the evaporation successful in term of covered areas.

The next step is to measure the coating thickness with the help of a profilometer. Indeed, due to FIRST laboratory intern policy, only 200 nm per material per user can be deposited in one run. As the trap was rotating all along the evaporation, the faces was not exposed all the time and the coating is probably thinner than the 300 nm (100 nm titanium and 200 nm gold) we expect.



Figure 4.12: Overlook of the trap nb.1 after evaporation coating of 100 nm of titanium and 200 nm of gold.

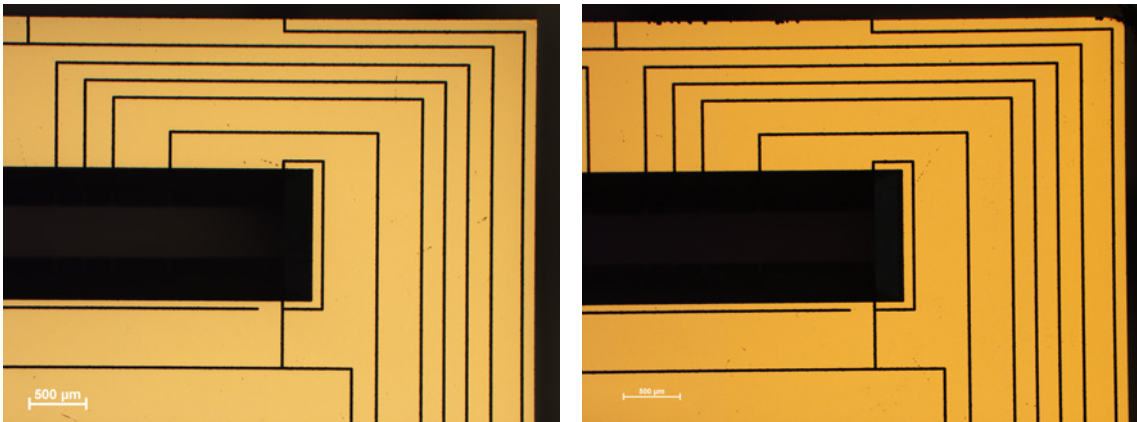
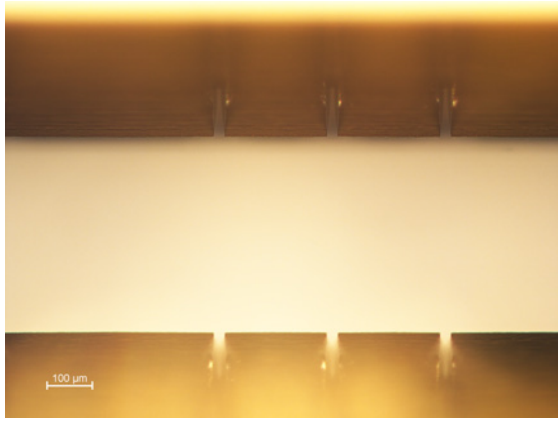
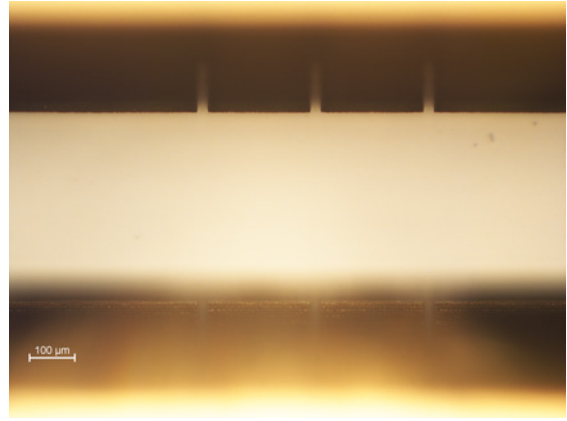


Figure 4.13: Top right corner of the traps Nb.1 (Left) and Nb.2 (Right) after coating by evaporation of 100 nm of titanium and 200 nm of gold.. Objective 2.5x.



(a) First set (10x)



(b) Second set (10x)



(c) First set (20x)



(d) Second set (20x)

Figure 4.14: Electrodes of the Trap nb.1 after evaporation. The different sets correspond to the pair of electrodes at different focal length. Objective 2.5x.

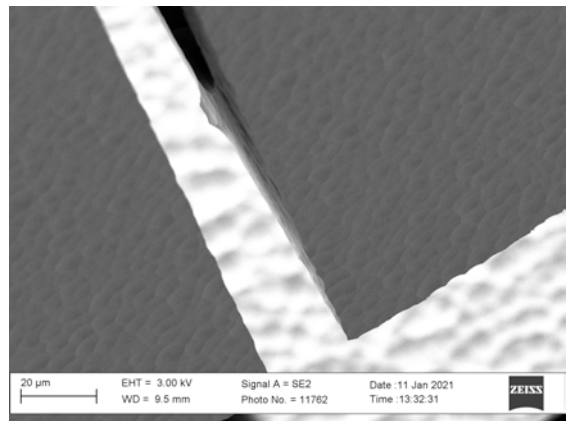
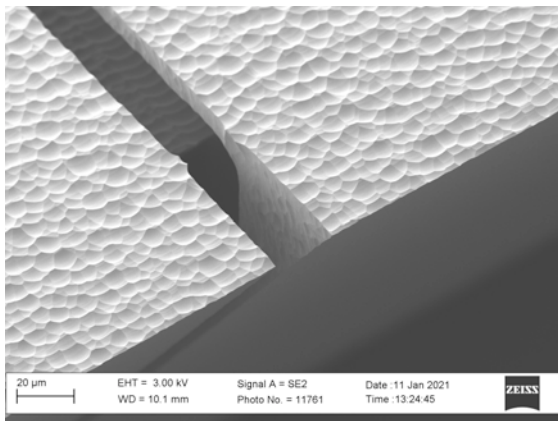


Figure 4.15: Scanning Electron Microscopy (SEM) pictures of the trap nb.1. After evaporation coating of 100 nm titanium and 200 nm gold on top. The coating has been process after piranha cleaning of the part.

The figure 4.16 shows the results of the profilometer on the trap nb. 2. The measurement consist of a beam holding a tip which move along the surface of the sample at a fixed distance. The thickness at the starting point is used as reference. When the tip while moving encounter surface changes, it induces deformations of the beam which can be converted in thickness values. The measurements were performed from the bottom (non coated area) to the top of the trap on its left and right sides (Fig.4.12). Following this pattern, the tip moved from non-coated to coated areas and allow us to have an estimation of the coating thickness by looking at the step profile. Furthermore, the profile was established until the area were the wire bonding has to be proceed.

From figure 4.16, we can extract a thickness of 245 nm on the left side of the trap (4.16a) and 170 nm on its right side (4.16b). As expected, these values are smaller that the one fixed in the evaporation recipe (300 nm in total) because the trap faces were not continuously exposed to the evaporation flux. We also notice a disparity in thickness between the two sides of the trap. It can be explained by the design of the holder which expose more the left than the right area of the trap during the evaporation. Another remark is that the coating thickness flatten after 1.6 mm on the right side while it is still increasing after 2 mm on the left side. A possible explanation could be that, since the top of the trap is the most exposed area (coated during the two runs), there is a thickness gradient from bottom to top which is more perceptible on the side with thicker coating. Please notice that the peaks in the plots are due to dirt or scratches and can be ignored.

Finally, the thickness inhomogeneity should not be problematic for ion trapping. However, it could leads to a more challenging wire bonding on the areas of low coating thickness. In fact, a too thin coating can be ripped-out from the trap surface by the wire bonding tip and prevent us to makes bonds.

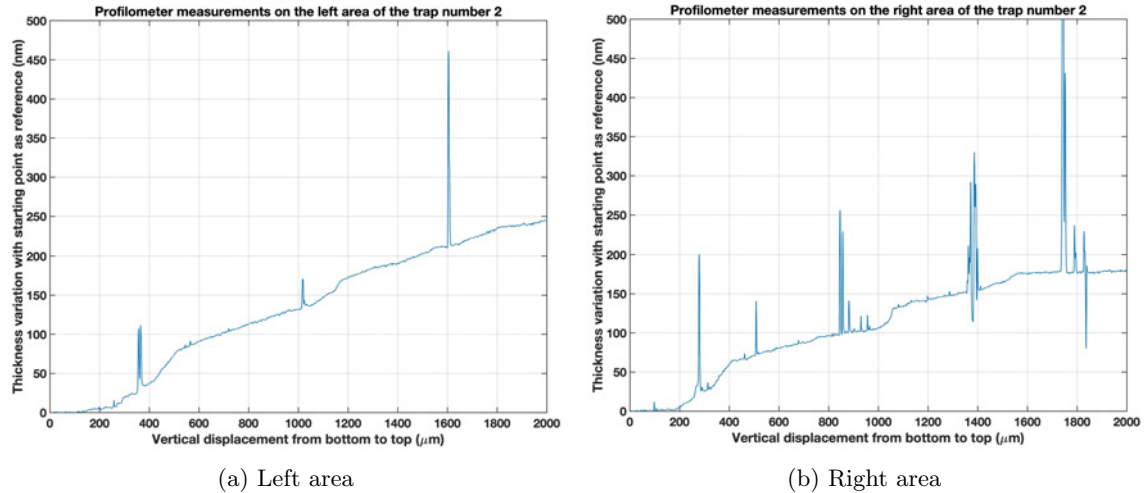


Figure 4.16: Thickness profile measured with profilometer on the left and the right of the trap nb.2. The reference height is the bottom area which was hided during the evaporation.

4.5.4 Coating failures

Failures have to be reported after several evaporation on the same trap. Indeed, the first coating on the trap nb.3 and nb.4 went out during the titanium etching bath proceeded to insulate the electrodes (see section 4.6). According to the process flow, gold and titanium etching bath was operated on the traps, followed by a piranha cleaning to prepare them for a new evaporation run. It happened that the quality of the coating decreased after each iteration of the process. Indeed, we observed the apparition of bubbles in the coating. This is particularly problematic since it makes the titanium accessible through the gold layer and avoid us to make the proper insulation of the electrodes. A suitable coating is illustrated in figure 4.17a while a failed deposition is shown in figure 4.17b.

A successful coating was finally achieved by first proceeding a standard Acetone-IPA-Water cleaning after the etching steps. In addition, two long DI water rinsing steps were performed. One following the etching baths and another after the piranha cleaning. They consisted in 30 min DI water at 50 °C with ultrasonic power at level 3. Furthermore, the drying steps were extended up to 10 min per traps of nitrogen gun. Finally the traps stayed at rest in a clean box for four days. The explanation from these outcomes is that contamination due to the etching steps was probably sitting in the trenches of the trap. Once in the vacuum chamber, the contaminant went out of the trenches and diffused on the trap surface. This led to more and more coating defects over time. Making long rinsing with ultrasonic power allowed us to well remove the acid from the trenches and to perform a good coating once the parts dried.

Another interesting approach would be to use the ion gun present in the Plassys II. This feature is present on some evaporation machines to do a cleaning of the sample surface directly inside the vacuum chamber by ion bombardment. It leads to substrate activation and therefore to better coating adhesion. However, the ion gun in Plassys II was not available at the time of this project.

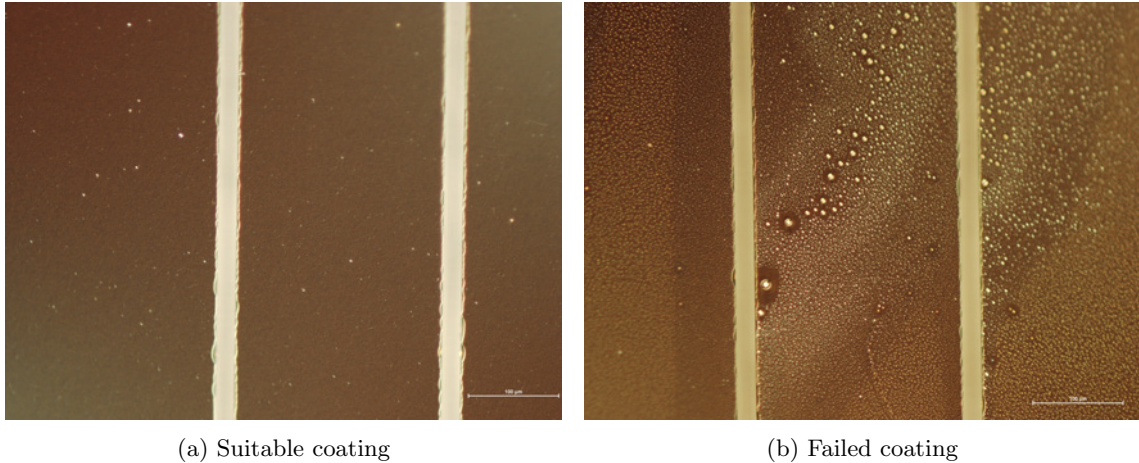


Figure 4.17: Optical pictures of trap nb.4 surface with Normaski filter to increase the contrast from surface roughness. (a) Picture of the successful coating after additional cleaning steps. (b) Pictures of a failed coating after standard etching and cleaning procedure. Objective 20x.

4.6 Electrical probing

Electrical probing consist in contacting metal tips on each gold electrodes to measure the resistance between them. A two-point measurement technique was used in this project. Indeed, we only want to check if the electrodes are insulated and not to find precise resistance values. In our case, the resistance of the metal tips is approximately $5\ \Omega$. This value therefore correspond to the resistance measured in case of short-circuit in the trap. Furthermore, we consider that the electrodes are insulated if the resistance between them is higher than $1 \times 10^8\ \Omega$. Indeed, higher value don't have a strong meaning because we reach the limit of the equipment in term of current measurement. Finally, the trap is placed on a glass microscope slide to avoid connections to the housing of the DC prober.

To investigate the connections, we first measured the resistance between all the pairs of neighbouring electrodes. In a second step, we consider the connections of each electrode to the ground. The ground corresponds to the square feature at the right-bottom of the trap which is linked to the bottom of the trenches. Please refer to the drawing in Appendix A. If any electrode has small resistance value to this ground, that mean it is somewhere connected to the bottom of one trench.

The results on the trap nb. 2 are presented in tables 4.1 and 4.2. We can notice that after the evaporation most of the trap electrodes were short circuited. However, the resistance value of the connection is around $1\text{ k}\Omega$. This is particularly unusual for gold since it is a highly conductive material. Even a very thin gold should not be able to achieve such high resistance values. A possible explanation is that diffusion of gold and titanium atoms occur inside the trench creating an atomic discontinuous layer. One solution to this problem was to do a titanium etching. Since the diffusion layer should be a mix of titanium and gold atoms, etching the titanium away would be sufficient to break the electrical connection. This technique was successful for most of the electrodes (Tables 4.1 and 4.2). However, few electrodes were still connected. We can notice that the last electrodes cannot be insulated this way because the second iteration of titanium etching bath did not improve the results. Probably these areas was more exposed during evaporation and there is enough diffused gold atoms to maintain an electrical connection without titanium. For these last electrodes, a non-conventional method which consist in applying current and voltage around 1 A and 10 V to burn the connection was performed. Please notice that this technique is currently used as last alternative for ion trap fabrication.

Connection between electrodes	Resistance (Ω) after evaporation	Resistance (Ω) after 1 st Ti etching	Resistance (Ω) after 2 nd Ti etching
1 to 2	9.82E+02	1.37E+09	8.90E+09
2 to 3	9.69E+02	3.00E+09	3.84E+10
3 to 4	9.57E+02	1.03E+10	1.35E+10
4 to 5	1.85E+03	5.87E+09	1.68E+10
5 to 6	2.72E+03	5.07E+09	5.10E+10
5 to 7	2.57E+04	8.90E+09	1.36E+09
7 to RF1	1.60E+10	1.52E+10	2.06E+10
7 to 8	2.58E+04	3.30E+09	4.55E+10
RF1 to 9	9.15E+09	5.44E+10	5.10E+10
9 to 10	1.86E+03	2.27E+10	3.08E+10
10 to 11	1.58E+03	2.46E+10	1.39E+10
11 to 12	1.39E+03	1.03E+10	1.22E+10
12 to 13	1.84E+03	8.11E+09	2.04E+09
13 to 14	1.56E+03	6.87E+09	7.8E+09
14 to 15	4.97E+03	3.38E+09	5.90E+10
15 to 16	5.55E+03	5.13E+09	3.13E+09
16 to 17	1.37E+04	4.13E+10	8.60E+09
17 to RF1	5.12E+09	5.38E+09	9.14E+09
RF1 to RF2	1.78E+10	4.81E+10	6.02E+10
RF1 to RF3	1.87E+09	1.52E+10	1.47E+10
RF2-RF3	2.40E+03	1.06E+11	6.3E+09
18 to RF3	1.34E+03	4.63E+10	4.50E+10
19 to RF3	1.39E+03	1.43E+10	2.41E+10
18 to 19	1.03E+03	9.40E+10	3.30E+10
19 to 20	8.67E+02	1.38E+10	1.05E+09
20 to 21	9.64E+02	2.87E+10	3.50E+10
21 to 22	1.32E+03	3.77E+08	1.74E+10
22 to 23	8.61E+02	1.83E+10	2.10E+10
23 to 24	3.46E+02	1.67E+03	2.69E+03

Table 4.1: DC probing between neighbouring electrodes for the trap nb. 2. Before and after titanium wet etching.

Connection to GND	Resistance (Ω) after evaporation	Resistance (Ω) after 1 st Ti etching	Resistance (Ω) after 2 nd Ti etching
1	6.16E+02	1.40E+03	5.80E+03
2	8.93E+02	7.89E+11	5.5E+10
3	9.42E+02	2.92E+10	1.20E+10
4	1.00E+03	9.37E+09	8.30E+09
5	1.73E+03	6.88E+09	1.59E+10
6	1.46E+03	1.65E+09	1.80E+12
7	2.59E+04	9.30E+09	2.90E+10
8	6.88E+02	6.87E+08	2.25E+10
RF1	4.15E+10	2.70E+12	8.27E+09
9	2.01E+03	7.90E+09	9.30E+08
10	2.04E+03	7.37E+09	1.76E+10
11	1.64E+03	4.70E+09	2.54E+10
12	1.65E+03	2.28E+10	1.89E+10
13	1.79E+03	1.53E+10	4.70E+12
14	1.84E+03	6.06E+09	8.20E+09
15	4.83E+03	2.55E+09	7.36E+09
16	2.29E+03	2.89E+09	3.40E+09
17	1.59E+04	2.76E+09	1.51E+10
RF2	2.08E+03	1.07E+10	1.00E+10
RF3	8.57E+02	1.59E+03	2.06E+03
18	7.25E+02	1.85E+10	1.46E+09
19	7.49E+02	1.29E+10	1.33E+10
20	7.52E+02	4.88E+09	4.00E+10
21	7.70E+02	4.98E+09	4.40E+09
22	8.94E+02	4.61E+09	3.2E+12
23	3.83E+02	5.64E+02	5.64E+02
24	3.31E+02	1.30E+03	1.90E+03

Table 4.2: DC probing to GND for the trap nb. 2. Before and after titanium wet etching.

4.7 Wire bonding

Wire bonding is a currently used method to connect a micro-scale device to its control electronics. It consist of making electrical connections by using metals wires with a diameter in the order a few microns. Several technology exits for contacting the bonds, the one in consideration for this project is ‘Wedge bonding’ and relies on application of ultrasonic power and force to press a wire onto the substrate.

4.7.1 Maximum current in wire bonds and material choice

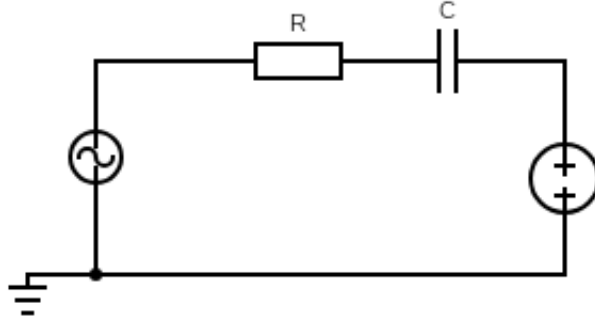


Figure 4.18: Equivalent circuit of the electrodes. R correspond to the resistance of the wire bond and C to the capacitance between RF electrodes and DC electrodes of the trap. This figure was created with Circuit Diagram web editor³.

The figure 4.18 described the equivalent electronic circuit of the trap electrodes. In this context, we would like to know the amplitude of the current to investigate how many bonds we need on the RF electrodes and in which material. Due to the capacitance, the DC contribution to the current is null. Please notice that here the imaginary number is named j instead of i as often done in electronics to not be confused with the current. Considering the voltage of the RF source:

$$u_{rf}(t) = U_{rf}e^{j\omega t} \quad (4.9)$$

The total impedance of the circuit is:

$$\bar{Z} = R + \frac{1}{j\omega C} = \frac{1 + j\omega RC}{j\omega C} \quad (4.10)$$

From Ohm’s law, we find the following expression for the current.

$$i(t) = \frac{u_{rf}(t)}{\bar{Z}} = \frac{j\omega C}{1 + j\omega RC} U_{rf}e^{j\omega t} \quad (4.11)$$

Isolating the amplitude and the phase of the impedance, we obtain:

$$i(t) = \frac{\omega C}{\sqrt{1 + \omega^2 R^2 C^2}} U_{rf} e^{j\omega t + \phi} \quad (4.12)$$

³<https://www.circuit-diagram.org/editor>

Numerical calculation

Two materials are in consideration according to FIRST equipment: gold or aluminium. From the table 4.19, we can extract the bonds resistivity. The idea here is to investigate the total current in the wire, the difference between gold and aluminum and to deduce the number of wire per pads. This must be done for the parameters of our setup and for the PSI - Paul Scherrer Institut - parameters. As assumption, we can consider wire bonds of maximum 5 mm length, the capacitance between RF and DC electrodes is around 2 pF and the diameters of the cable according to the machine parameters is 25 μm (≈ 1 mils). This leads to the following resistance values: $R_{alu} = 0.262 \Omega$ and $R_{gold} = 0.229 \Omega$. The parameters are the followings.

TIQI parameters

- $U_{rf} = 50 \text{ V}$
- $\omega = 2\pi \cdot 50 \text{ MHz}$

PSI parameters

- $U_{rf} = 400 \text{ V}$
- $\omega = 2\pi \cdot 35 \text{ MHz}$

Considering only one wire, the maximum value of the current is very similar for aluminium and gold and the values are:

$$I_{max, TIQI} = 3.14 \text{ mA} \quad I_{max, PSI} = 175.9 \text{ mA} \quad (4.13)$$

These current intensities are reasonable. We can conclude that in term of current, aluminum and gold wire will give the same performance and only one wire bond per electrode is required. The choice between gold and aluminum wires has to be done on other criteria. One can notice that aluminum bonds very well on gold substrate, without heating the sample. However, it occurs that aluminum wire on gold tends to build some brittle inter-metallic phase when exposed over long time to elevated temperature, as it was already observed in previous experiments in the laboratory. Since the chamber, where the trap take place, will be backed to achieve ultra-high vacuum (UHV), **gold wire bonds is the final choice.**

Wire Type	Diameter (mils)	Wire Area (mils ²)	Resistivity (Ω/inch)	Typical DC Fusing Current (amps)	Recommended Bond Pad Size (mils)
Gold	1.00	0.79	1.16	0.6-0.7	4 x 4
	1.30	1.33	0.693	0.9-1.0	5 x 5
	1.50	1.77	0.521	1.2-1.4	6 x 6
	2.00	3.14	0.294	1.6-2.0	8 x 8
Aluminum	1.00	0.79	1.33	0.27-0.30	3.5 x 3.5
	1.25	1.23	0.856	0.4-0.5	4 x 4
	1.50	1.77	0.595	0.6-0.7	6 x 6
	2.00	3.14	0.335	1.0-1.2	6 x 8
	3.00	7.07	0.149	2-2.5	9 x 12
	4.00	12.57	0.0838	3.5-4.0	12 x 20
	5.00	19.63	0.0537	5-6	15 x 25
	8.00	50.27	0.0210	11-12	20 x 32
	10.00	78.54	0.0134	16-18	25 x 40
	12.00	113.10	0.0093	21-23	30 x 48
	15.00	176.71	0.0059	20-35	40 x 60
	20.00	314.16	0.0033	50-60	50 x 80

Figure 4.19: Table of wire bonds resistivity for aluminum and gold.⁴

4.7.2 Wire bonding machine parameters

The gold bonder in FIRST cleanroom was used to do the wire bonding from the trap nb.2 to the PCB. To proceed, the trap and the PCB has been mounted on the dedicated holder which will take place in the experiment chamber (Section 3.3.3). At this stage of the fabrication, all the components and cables were already soldered to the PCB. This result in the design of a new part to be able to fix the assembly on the bonder hot plate. Indeed, to achieve adhesive bonds, the trap and the PCB has to be heated at 120 °C.

Since the holder is bulky, to have a good temperature on the trap, the hot plate is set at 135 °C considering the temperature gradient between the plate to the sample. The machine parameters for the wire bonding was found empirically by testing them on the trap nb. 1 and on a coated microscope slide. For this equipment (Westbond 747677E), the ultrasonic power is defined in arbitrary units on a range of 0 - 999. The result of the bonding is exposed in figure 4.20 and the parameters are:

- First bond on the trap: ultrasonic power 155, time 125 ms, force: LOW
- Second bond on the PCB: ultrasonic power 200, time 125 ms, force: HIGH

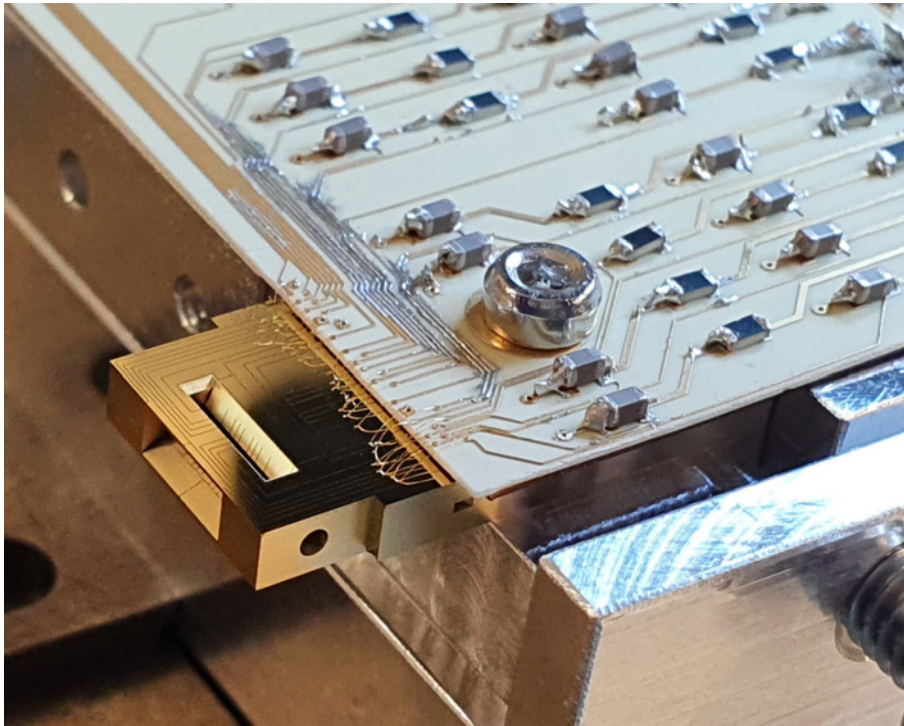


Figure 4.20: Result of the wire bonding. The trap (left) and the PCB (right) are assembled on the aluminium part designed to be in the vacuum chamber.

⁴<https://www.rfcafe.com/references/electrical/bond-wire-specs.htm>

4.8 Other fabrication techniques to explore

4.8.1 Collimated Sputtering

Sputtering is a well-established technique which consist in using plasma ion bombardment on a crucible. The molecules extracted from the crucible flows in the chamber and coat the sample. This technique as several benefits which are good adhesion, good film uniformity and the deposition of large amount of material. However, this technique can not be used in the case of our trap because the deposition is not directional and would indubitably coat also the inside of the trenches. This will result in short-circuits between all the trap electrodes.

However, the directionality of the deposition can be controlled by adding a grid in the chamber. Indeed, the molecules with a two high incidence angle are stopped by the grid while the other flies until the substrate. This technique is currently not available in FIRST cleanroom or in PSI. However, this could be a great process to improve the gold coating uniformity and thickness, while keeping the inside of the trenches unexposed.

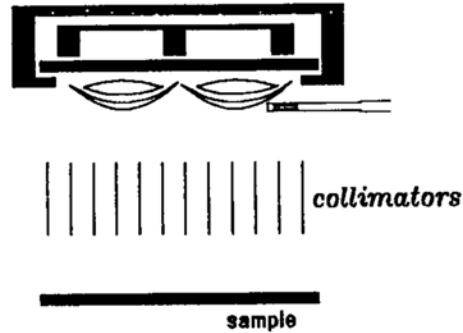


Figure 4.21: Illustration of the chamber for collimated sputtering process. This picture comes from the publication of S.M. Rossnagel and D. Mikalsen [18].

4.8.2 3D polymer structuring

The technique of 3D polymer structuring consist in building complex micro-structures in polymer with two photon absorption. This allows fabrication at sub-micron scale and can be a great technique for prototyping ion traps in low delay. Indeed, this fabrication can be carried out in PSI cleanroom with the use of the Nanoscribe GT machine. Please notice that the traps fabricated with this technique cannot be used in the final setup. Furthermore, due to the material, aggressive cleaning like piranha solution would dissolve the trap. However, I experience during this thesis the FEMTOPrint delay which are in the order of several weeks. To try many iterations of a trap design, for example of its trenches, this technique could be a suitable solution. Indeed, considering the trap fabricated during this project, proceeding evaporation coating on a polymer version of the trap would have told us about the molecular diffusion of the coating inside the trenches. In general, 3D polymer structuring could be an efficient way to test different trap design while saving time and money.

Summary and Outlook

In this work, the fabrication of a monolithic Paul Trap to couple negative and positive ions and its benefits for quantum information processing has been investigated. It started by considering a theoretical implementation of a new quantum charge-coupled device architecture in order to compute quantum algorithm. The analysis focused on the feasibility of quantum gates in a situation where the information is carried by negative ions which can only interact through an ancilla. The development of an equivalent circuit for Controlled-NOT gate using a positive ion as ancilla gave a primary proof of concept to realize a quantum computer using this innovative approach.

Then, we addressed the question of the advantages of this new architecture over the current ion trapping experiment that only use positively charged ions. In order to answer it, a Mathematica simulation of planar Paul Traps with optimized design has been developed. It leads to the conclusion that more scalable trapping potentials can be created by achieving small distances between ions with fairly low voltages. The results of this theoretical work justified the setting up of our experiment while giving encouraging perspectives about its expected outcomes for quantum information processing.

As the next step, a first iteration of the experimental setup has been designed. Several parts were drawn in order to place the ion trap at the conjunction of the beams installed in the vacuum chamber. Furthermore, an electron gun mount and an oven have been conceived in order to produce beryllium cation directly inside the trapping cavity, whereas deuterium anions would be able to flow inside the trap from its right opening. Finally, the last part to be designed was a PCB, which control and filter the voltage on the trap electrodes. This model is made in order to fit into the chamber and facilitate the wire bonding. To conclude, this realization gives an appropriated basis for building the experiment. This would be performed in the continuity of this project by new students in the group.

The last part of this thesis consisted in the fabrication of the monolithic Paul trap. The process flow followed throughout the project involves several cleanroom techniques regarding cleaning, etching, coating and wire bonding. As some issues have been observed, some additional steps were required compared to the initial process flow, more specially about the insulation of the electrodes. Indeed, the internal T-shape features, in their current design, were subject to diffusion and additional etching baths was needed. Nevertheless, the fabrication is a success and a reproducible working flow has been established. As conclusion of the fabrication, one advice would be to be careful in the use of trenches for future traps design because, as observed during this project, it can leads to additional wetness and contamination if several evaporation steps are required. The use of an evaporation mask can be a more suitable method if the design of the trap is not too complex.

To conclude, this project paved the way of building a new generation of trapped ions quantum devices, making use of both positive and negative ions.



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Appendix A

Trap Electrodes

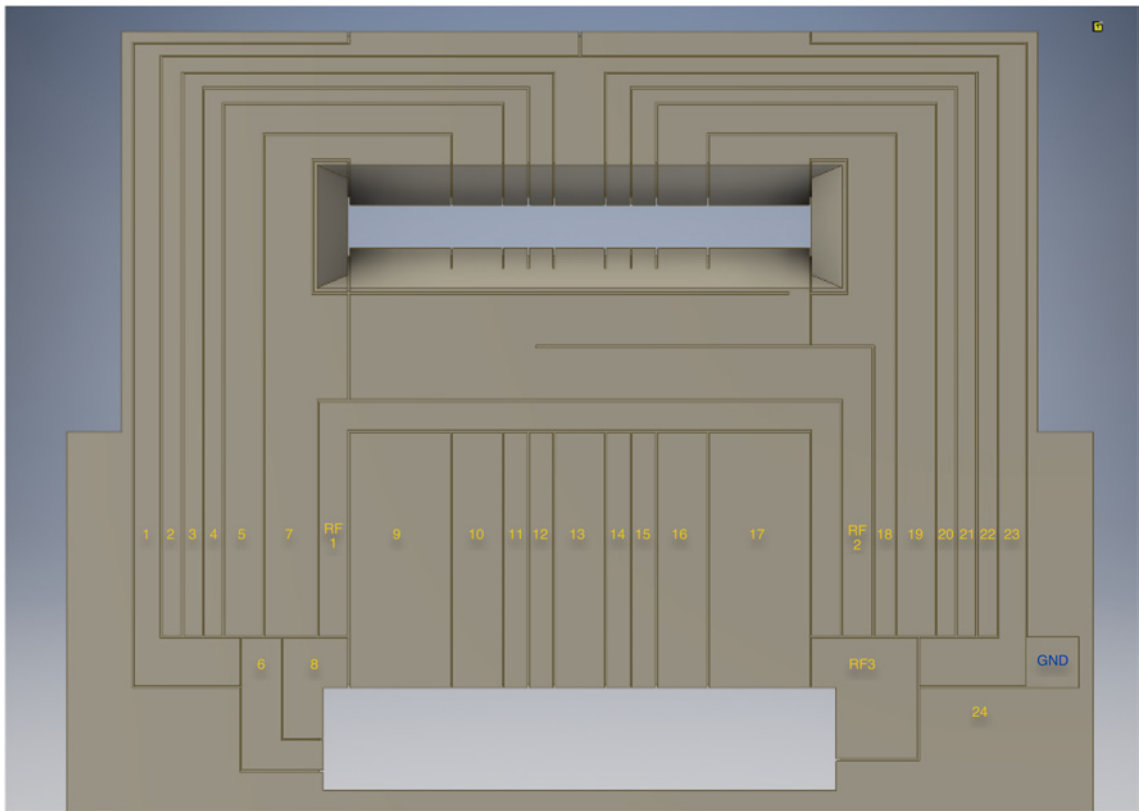


Figure A.1: Numbering of the trap electrodes.

Appendix B

Electrical probing results

Connection between electrodes	Resistance (Ω) after evaporation	Resistance (Ω) after 1 st Ti etching	Resistance (Ω) after 2 nd Ti etching
1 to 2	1.35E+03	5.40E+08	3.15E+10
2 to 3	1.14E+03	2.80E+11	2.00E+09
3 to 4	1.19E+03	8.50E+10	6.03E+09
4 to 5	1.97E+03	5.60E+10	7.06E+09
5 to 6	2.09E+03	2.08E+11	1.00E+11
5 to 7	4.01E+03	2.77E+11	4.57E+10
7 to RF1	2.86E+03	1.56E+11	9.20E+10
7 to 8	2.89E+03	5.30E+10	1.00E+11
RF1 to 9	1.25E+03	9.67E+08	1.47E+10
9 to 10	1.86E+03	2.40E+09	2.98E+13
10 to 11	1.47E+03	4.50E+03	4.90E+09
11 to 12	1.76E+03	2.07E+03	8.32E+08
12 to 13	2.18E+03	1.00E+09	1.93E+10
13 to 14	5.15E+03	4.70E+09	2.83E+10
14 to 15	7.18E+03	3.50E+09	2.36E+10
15 to 16	6.22E+03	1.14E+10	4.25E+10
16 to 17	1.39E+09	5.05E+08	8.26E+09
17 to RF1	1.53E+09	1.76E+09	1.58E+11
RF1 to RF2	1.14E+09	6.84E+08	9.17E+10
RF1 to RF3	8.49E+02	9.90E+03	1.40E+09
RF2-RF3	1.47E+09	3.00E+11	9.00E+11
18 to RF3	1.52E+03	1.10E+10	3.30E+10
19 to RF3	1.51E+03	3.97E+10	1.80E+9
18 to 19	1.27E+03	5.16E+10	3.20E+10
19 to 20	1.13E+03	2.10E+10	3.95E+10
20 to 21	1.08E+03	2.60E+10	1.89E+10
21 to 22	1.30E+03	1.16E+09	5.17E+10
22 to 23	1.02E+03	4.37E+11	8.1E+10
23 to 24	4.04E+02	4.30E+03	2.30E+03

Table B.1: DC probing between neighbours electrodes for the trap nb. 1. Before and after titanium wet etching.

Connection to GND	Resistance (Ω) after evaporation	Resistance (Ω) after 1 st Ti etching	Resistance (Ω) after 2 nd Ti etching
1	9.14E+02	1.70E+03	1.73E+03
2	9.93E+02	1.09E+10	1.35E+11
3	1.11E+03	7.56E+10	5.40E+09
4	1.23E+03	1.22E+10	5.30E+10
5	2.20E+03	1.07E+10	3.90E+10
6	5.07E+02	3.50E+03	4.67E+08
7	3.02E+03	2.33E+10	4.60E+10
8	4.92E+02	3.50E+03	5.75E+08
RF1	4.73E+02	5.32E+02	5.50E+02
9	1.61E+03	1.90E+09	2.79E+10
10	1.94E+03	6.30E+03	4.20E+09
11	1.62E+03	1.80E+03	4.35E+09
12	2.41E+03	1.39E+03	2.56E+03
13	1.91E+03	1.64E+09	8.60E+09
14	5.73E+03	1.90E+09	2.3E+10
15	3.76E+03	4.40E+09	3.89E+10
16	3.59E+03	1.69E+03	1.03E+10
17	1.87E+09	1.26E+09	7.90E+09
RF2	1.13E+09	3.45E+10	1.60E+09
RF3	8.45E+02	1.00E+04	1.39E+09
18	9.71E+02	5.50E+09	1.79E+10
19	9.21E+02	4.92E+11	9.70E+09
20	9.34E+02	3.40E+09	1.70E+09
21	9.07E+02	1.48E+04	1.46E+10
22	9.94E+02	4.78E+09	8.00E+10
23	4.58E+02	2.82E+03	9.96E+02
24	4.11E+02	2.07E+03	2.02E+03

Table B.2: DC probing to GND for the trap nb. 1. Before and after titanium wet etching.

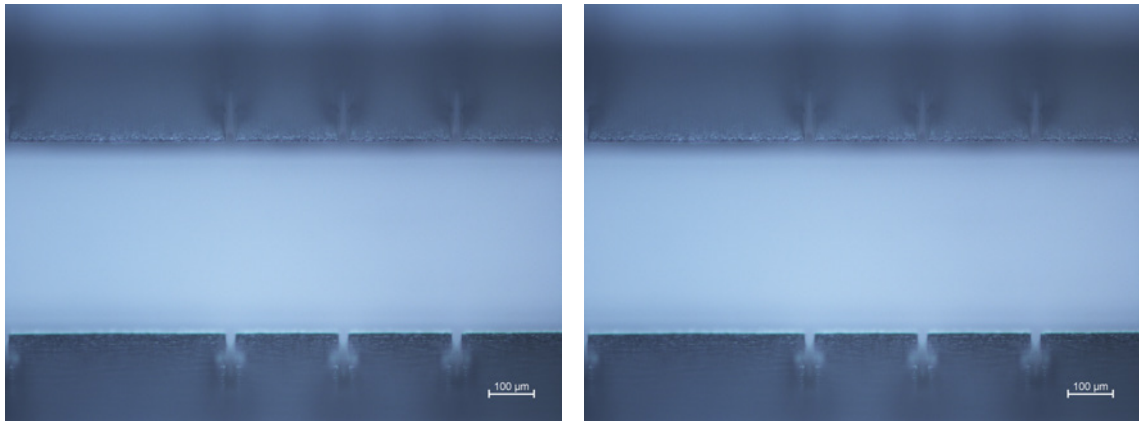
Appendix C

Microscopy review of the traps

C.1 Review of the glass parts

C.1.1 Optical pictures

Trap 1



(a) First set (10x)

(b) Second set (10x)

Figure C.1: Electrodes of trap nb. 1. After cleaning with Acetone-IPA-Water. Before evaporation.

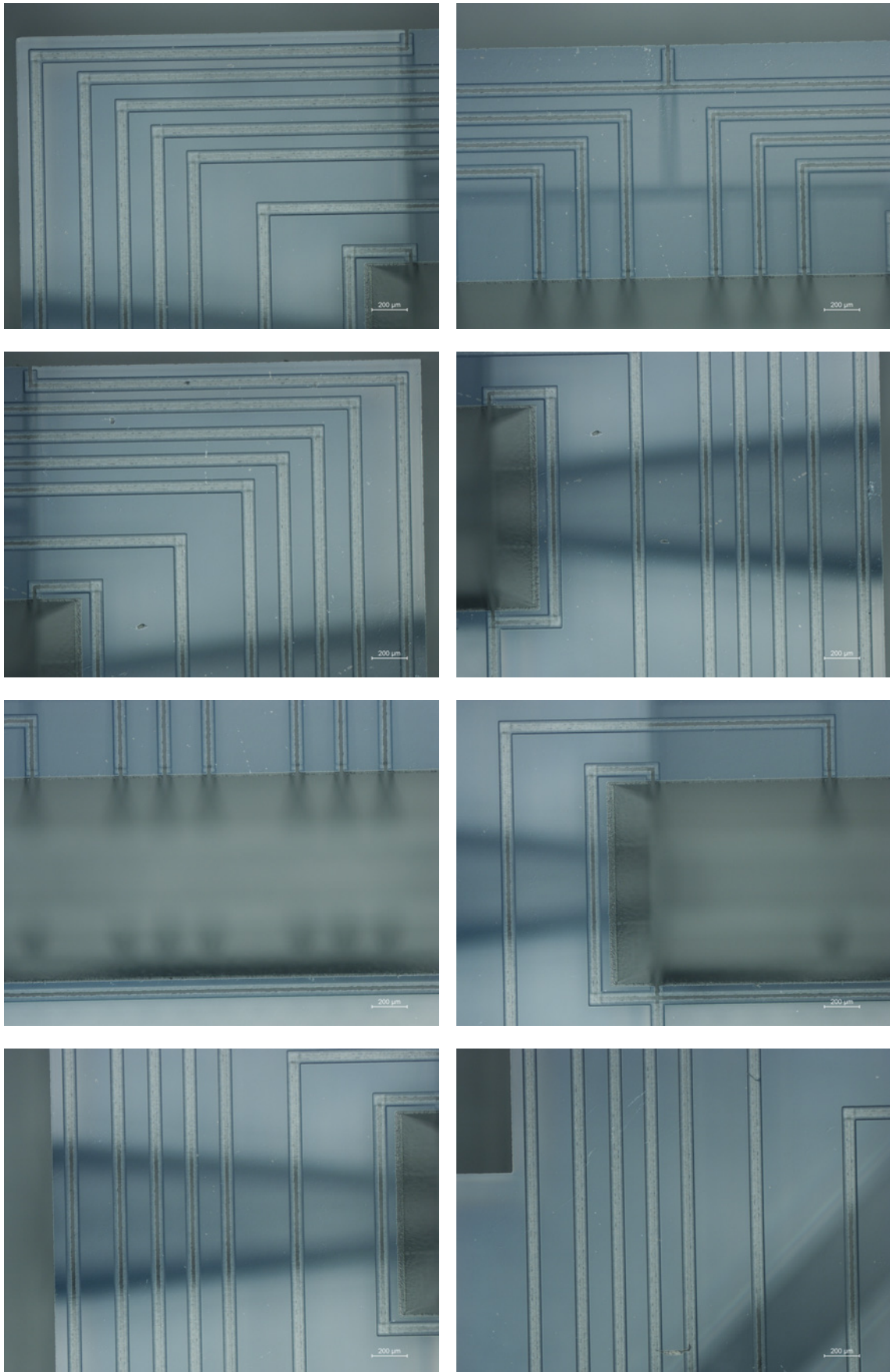


Figure C.2: Trap nb. 1 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.



Figure C.3: Trap nb. 1 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.

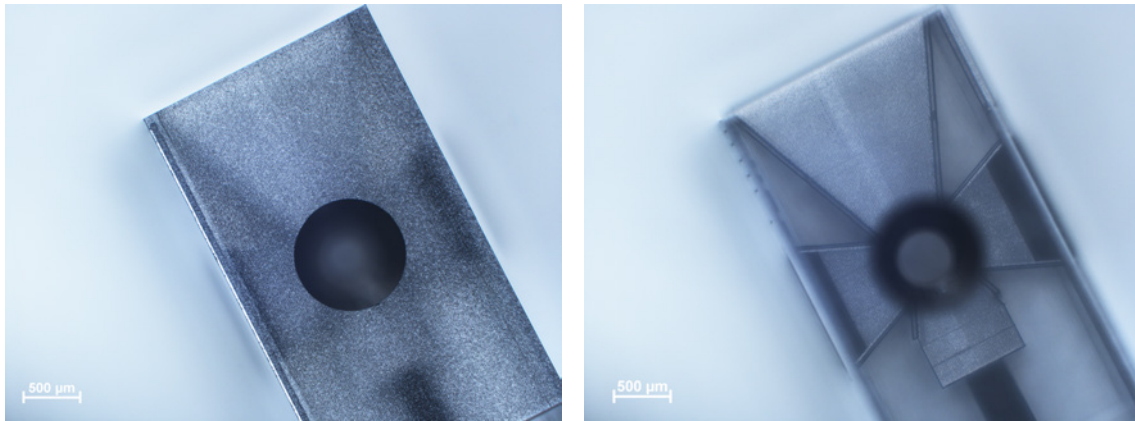


Figure C.4: Trap nb. 1 sides inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.

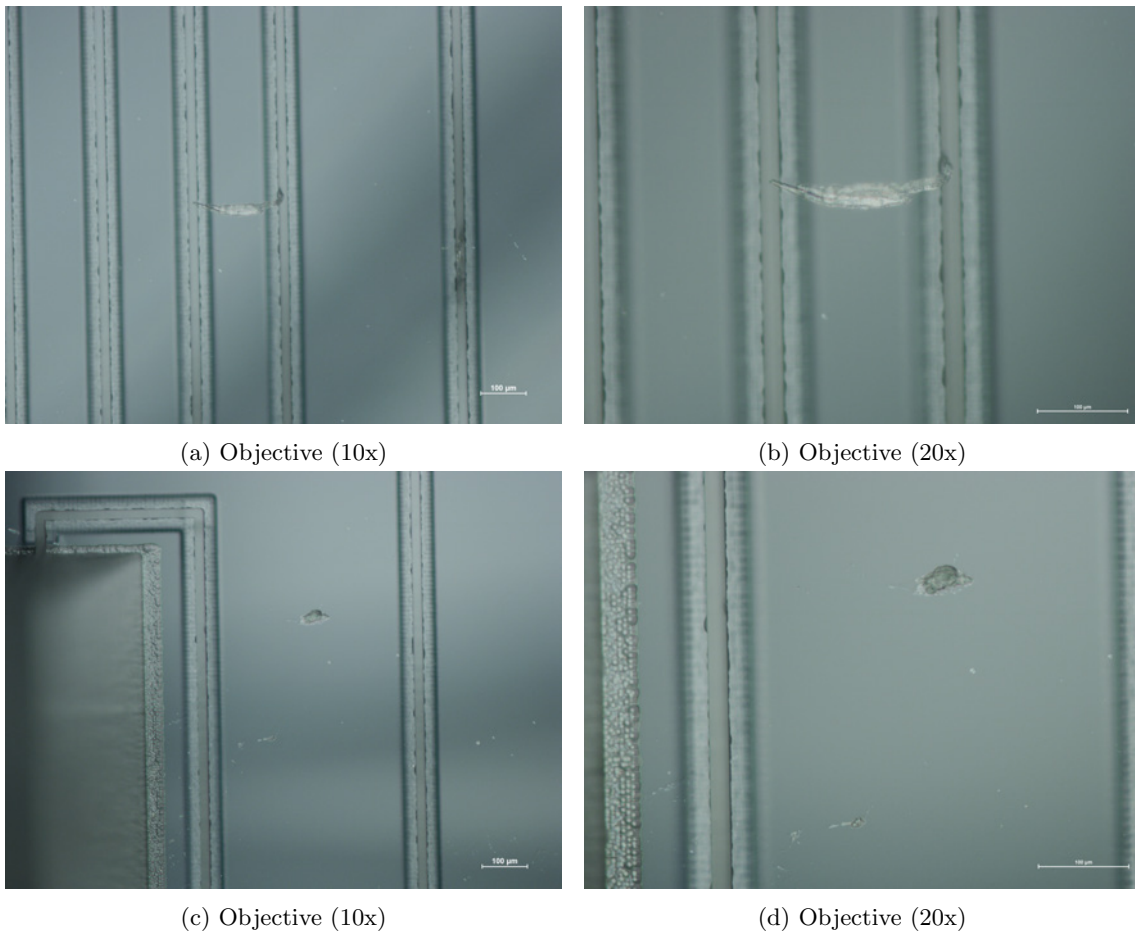
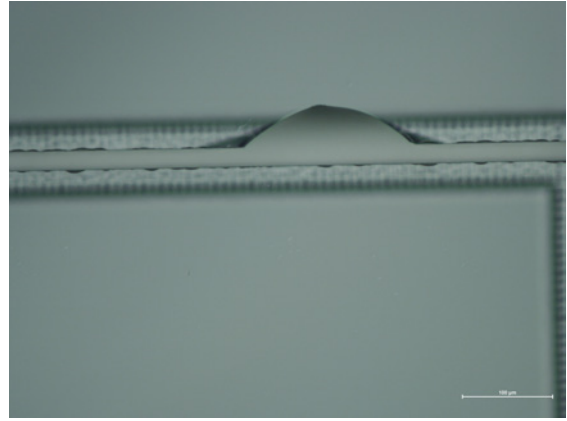


Figure C.5: Trap nb. 1 defects inspection after cleaning with Acetone-IPA-Water standard protocol.

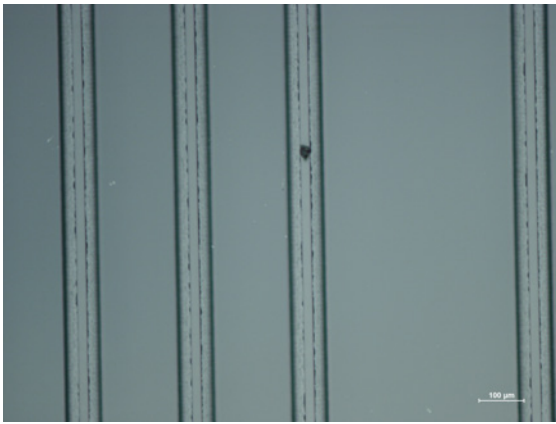


(a) Objective (10x)

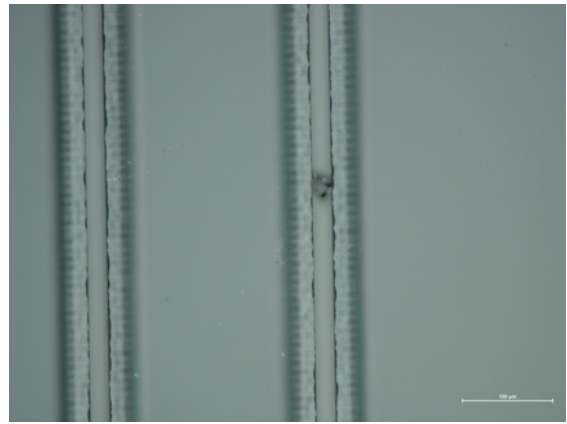


(b) Objective (20x)

Figure C.6: Trap nb. 1 defects inspection after cleaning with Acetone-IPA-Water standard protocol.



(a) Objective (10x)



(b) Objective (20x)

Figure C.7: Trap nb. 1 defects inspection after cleaning with Acetone-IPA-Water standard protocol.

Trap 2

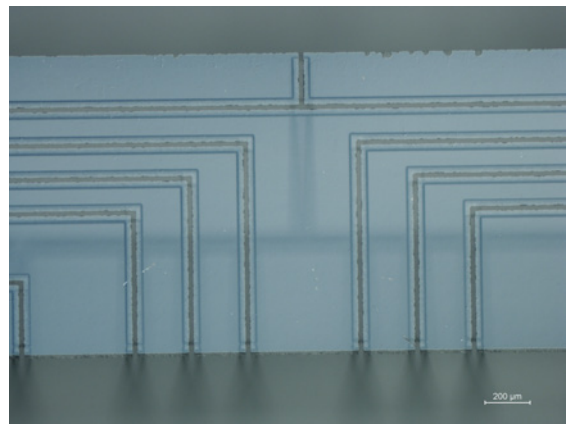
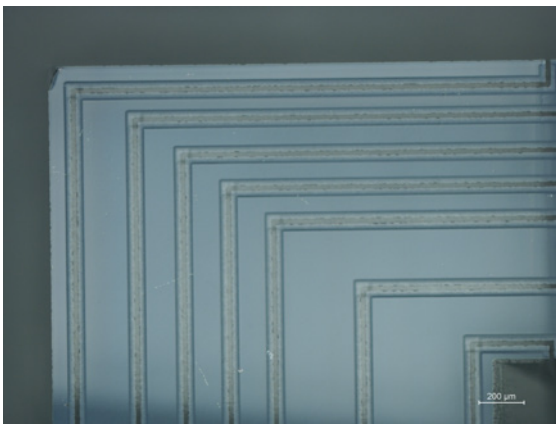


Figure C.8: Trap nb. 2 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.

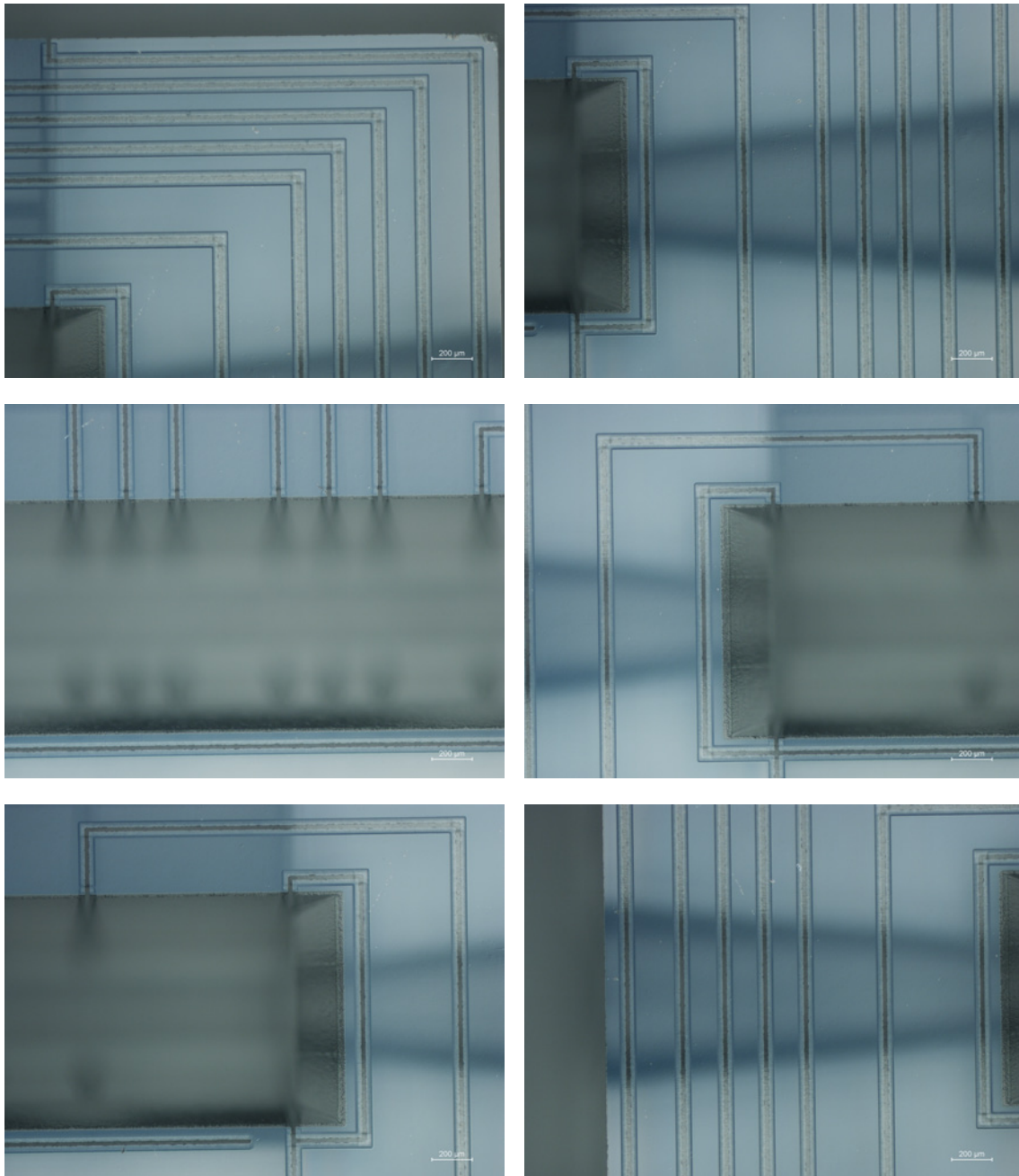


Figure C.9: Trap nb. 2 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.

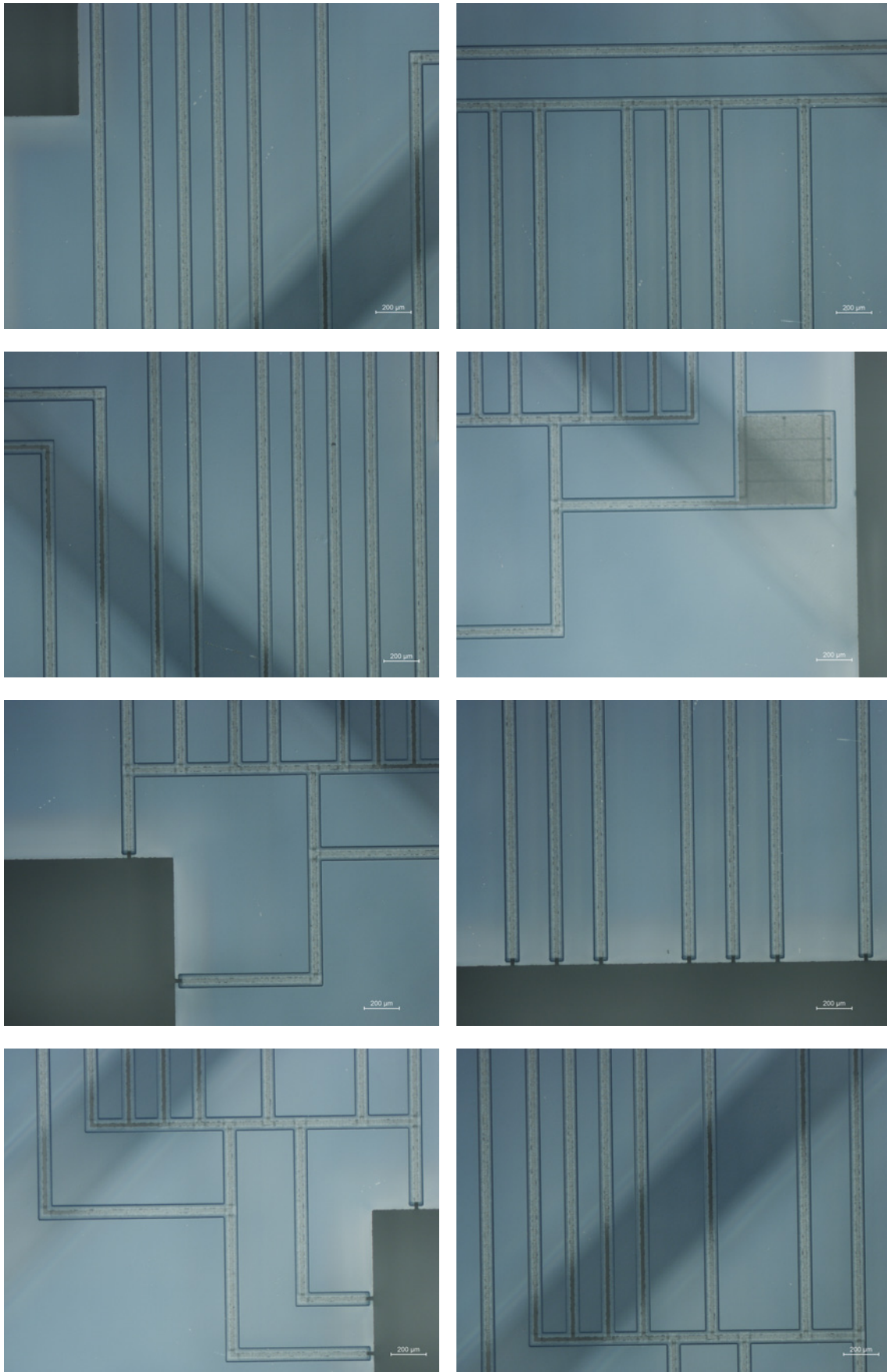
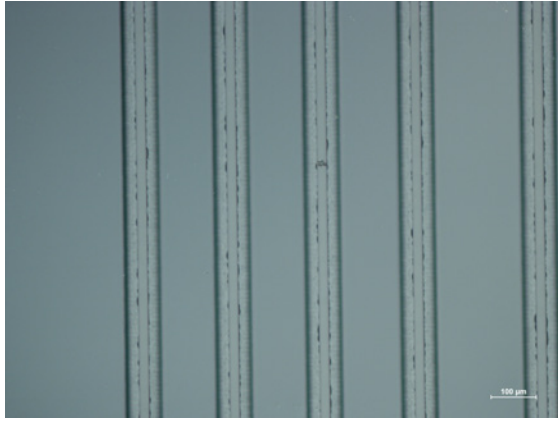
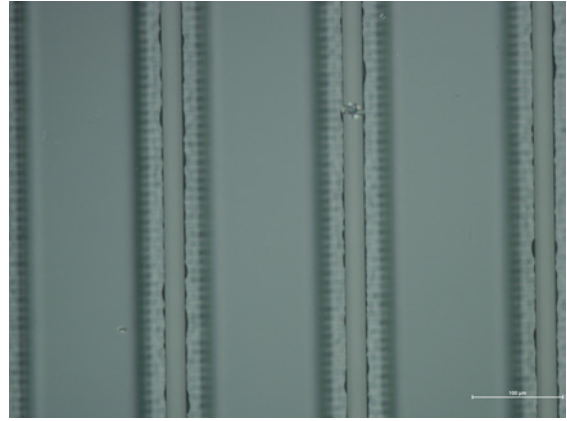


Figure C.10: Trap nb. 2 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.



(a) Objective (10x)



(b) Objective (20x)

Figure C.11: Trap nb. 2 defects inspection after cleaning with Acetone-IPA-Water standard protocol.

Trap 3

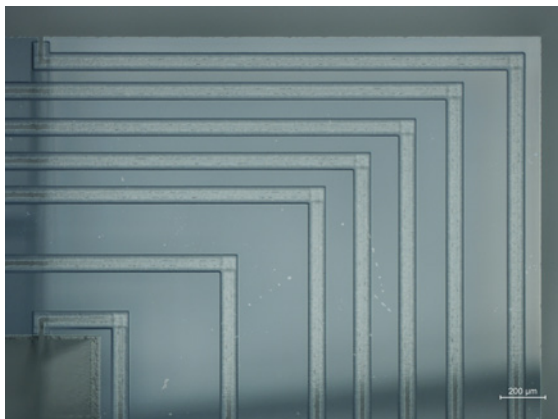
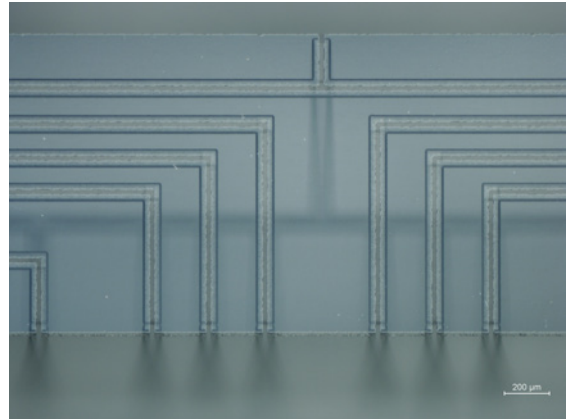


Figure C.12: Trap nb. 3 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.

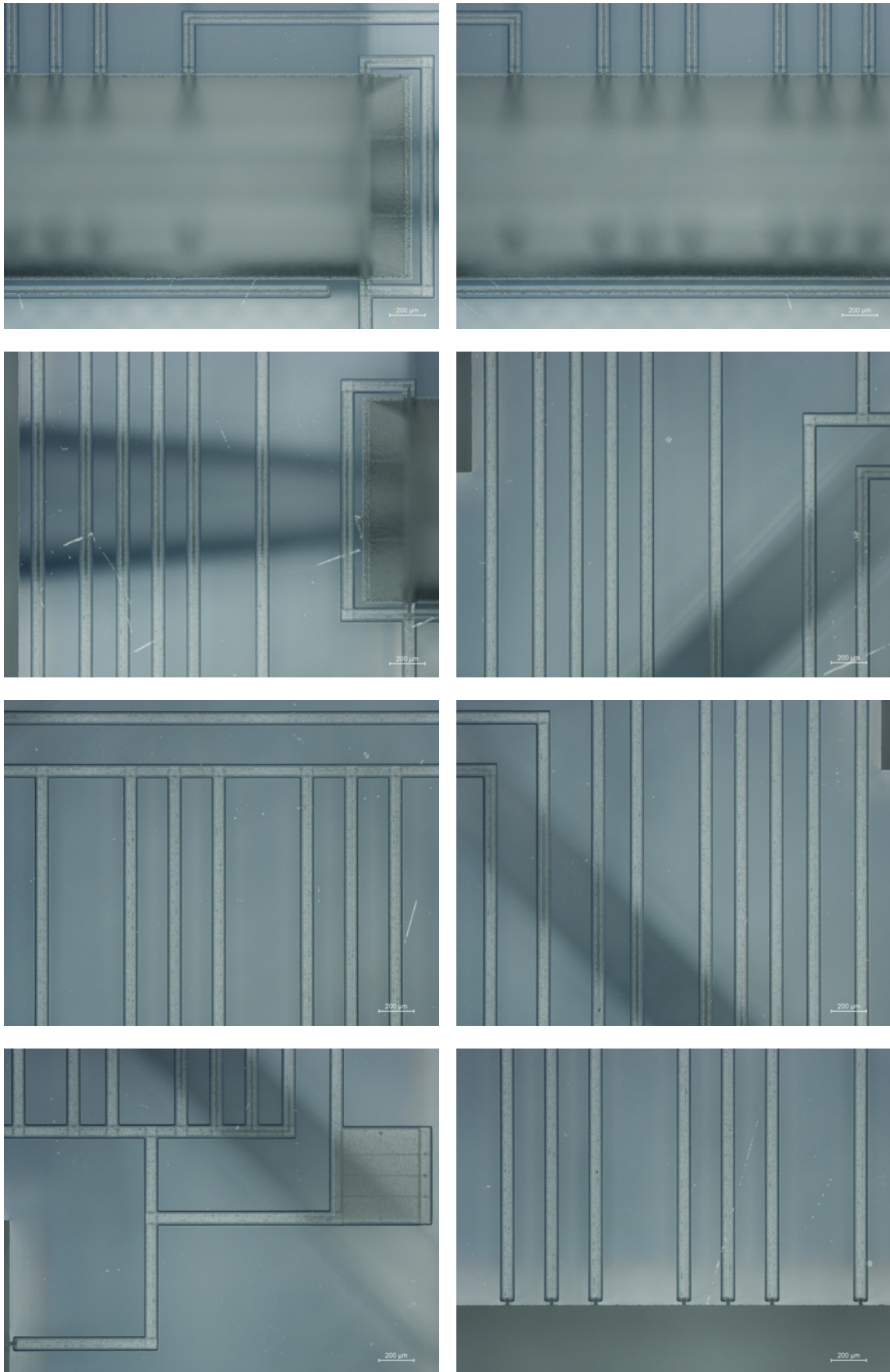
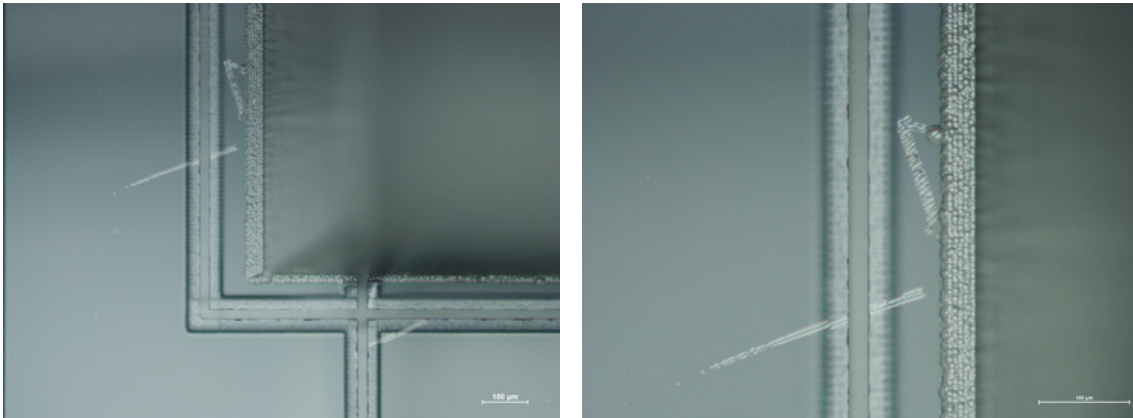


Figure C.13: Trap nb. 3 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.



Figure C.14: Trap nb. 3 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.



(a) Objective (10x)

(b) Objective (20x)

Figure C.15: Trap nb. 3 defects inspection after cleaning with Acetone-IPA-Water standard protocol.

Trap 4



Figure C.16: Trap nb. 4 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.

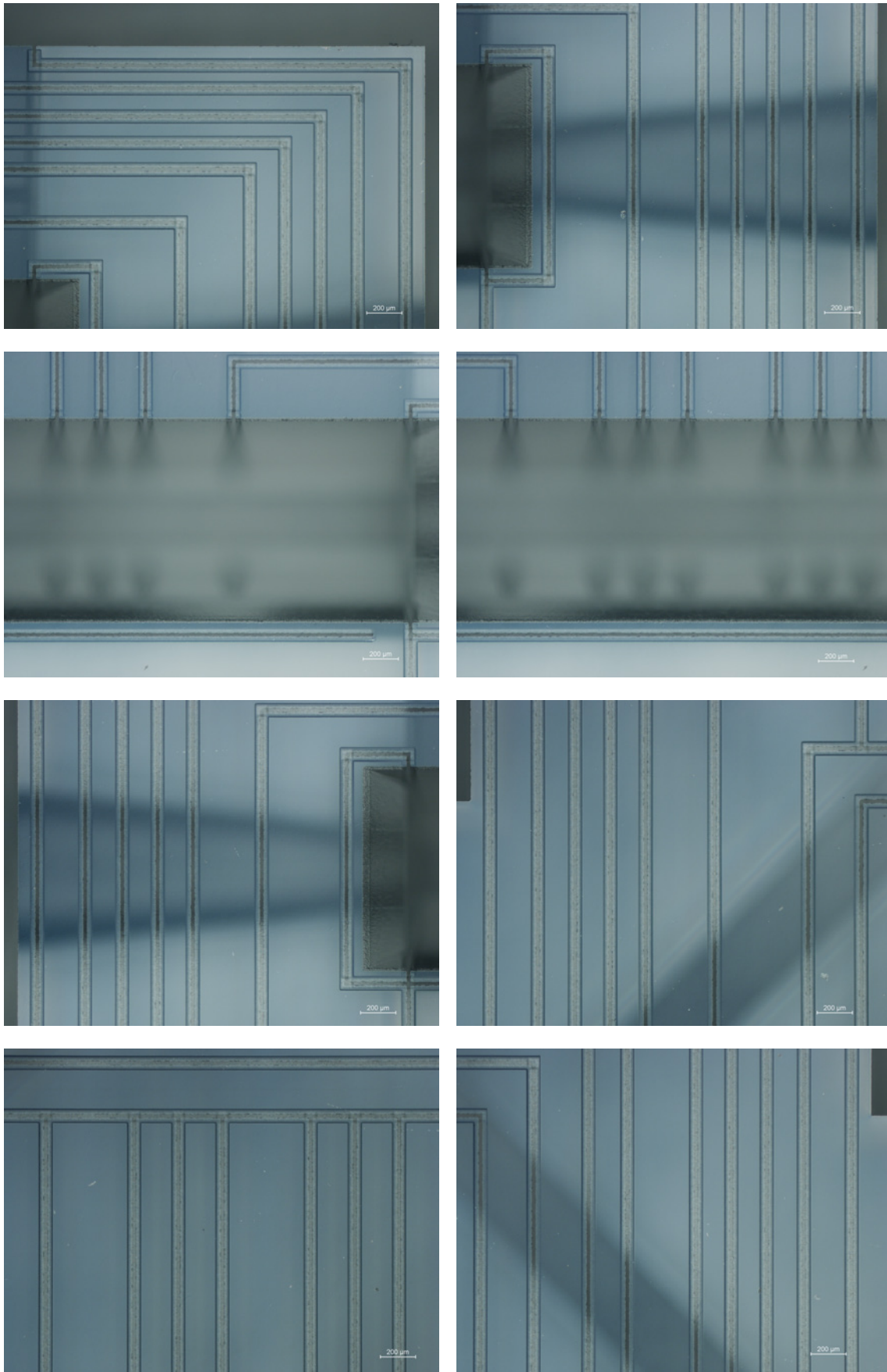


Figure C.17: Trap nb. 4 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.

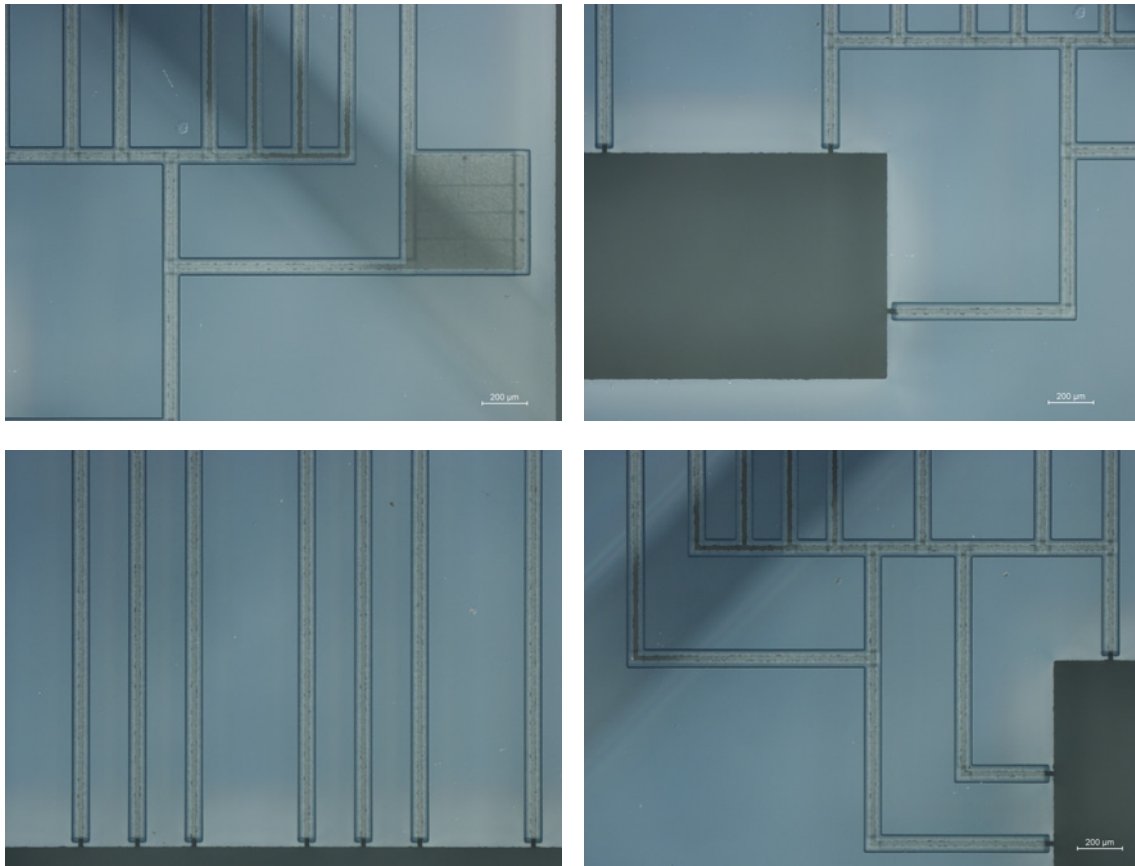
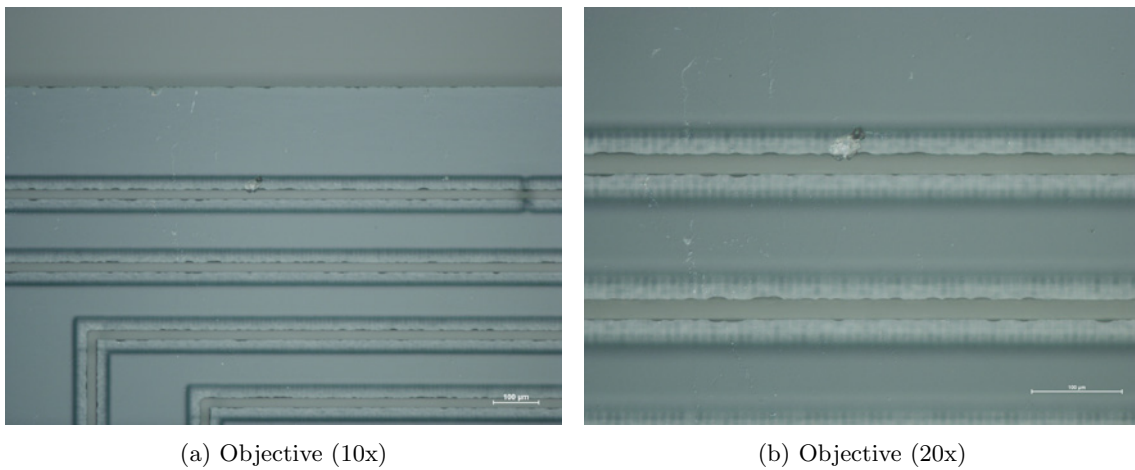


Figure C.18: Trap nb. 4 features inspection after cleaning with Acetone-IPA-Water standard protocol. Objective 5x.



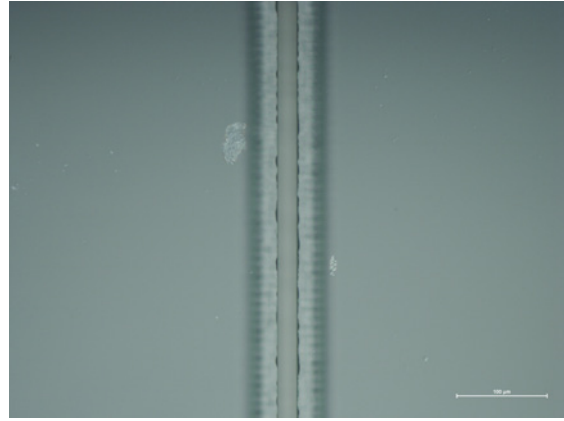
(a) Objective (10x)

(b) Objective (20x)

Figure C.19: Trap nb. 4 defects inspection after cleaning with Acetone-IPA-Water standard protocol.



(a) Objective (10x)



(b) Objective (20x)



(c) Objective (10x)



(d) Objective (20x)

Figure C.20: Trap nb. 4 defects inspection after cleaning with Acetone-IPA-Water standard protocol.

C.1.2 Normarski filter

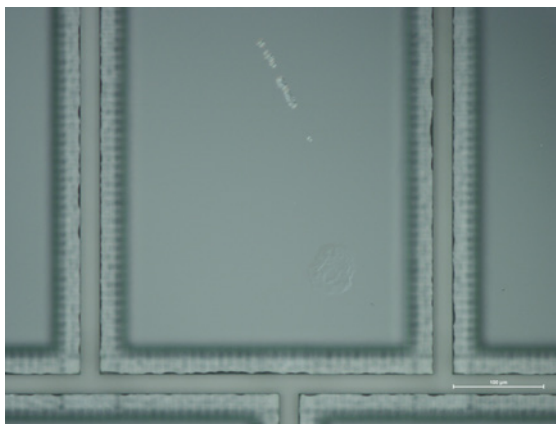


Figure C.21: Trap nb. 4 spotted defect with (left) and without (right) Normarski filter. This filter allows to transform surface relief into contrast. Objective 20x.

C.1.3 Scanning Electron Microscopy pictures

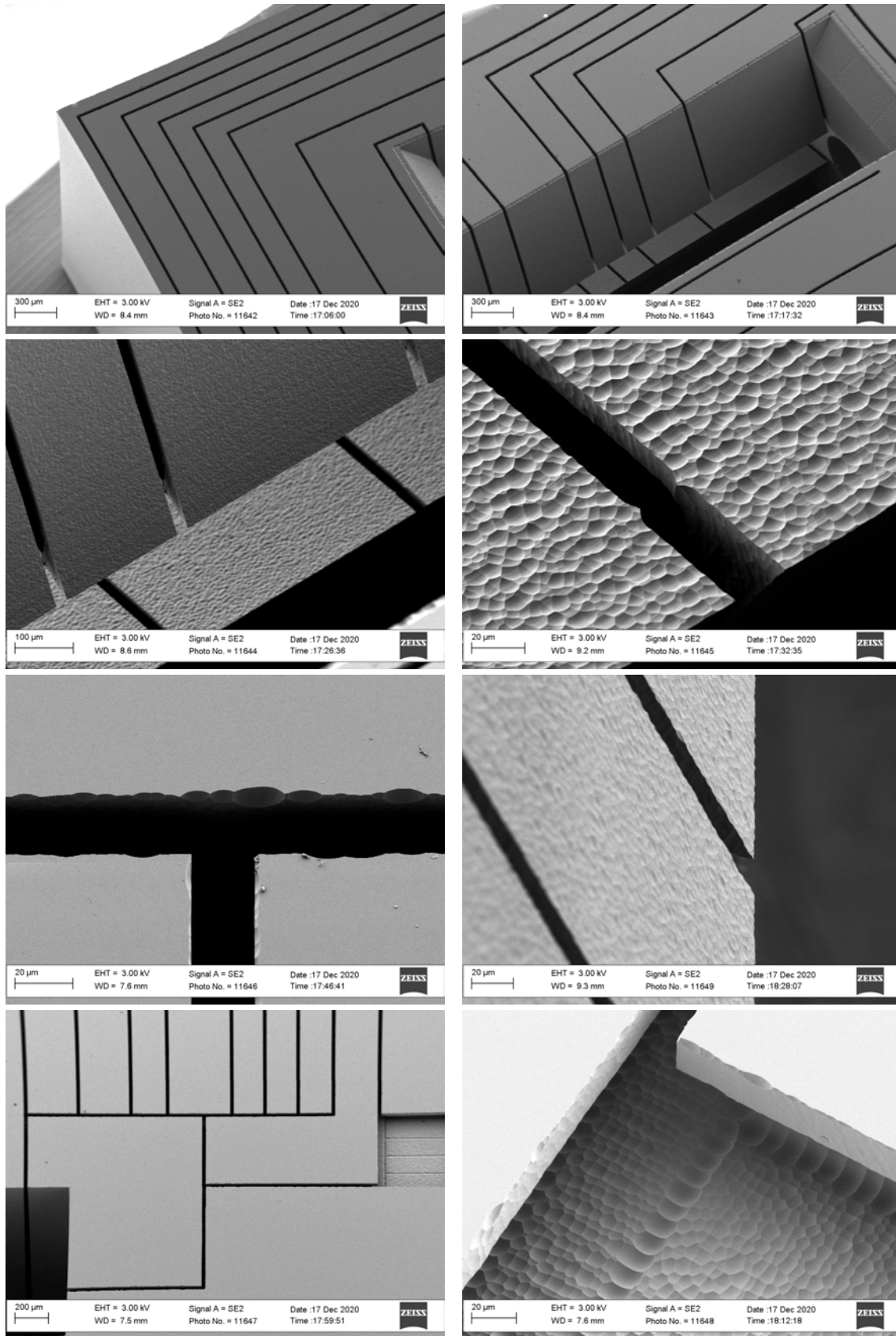


Figure C.22: Scanning Electron Microscopy (SEM) pictures of the trap nb.4 after standard Acetone-IPA-Water cleaning.

C.2 After evaporation

C.2.1 Optical microscopy

Trap 1

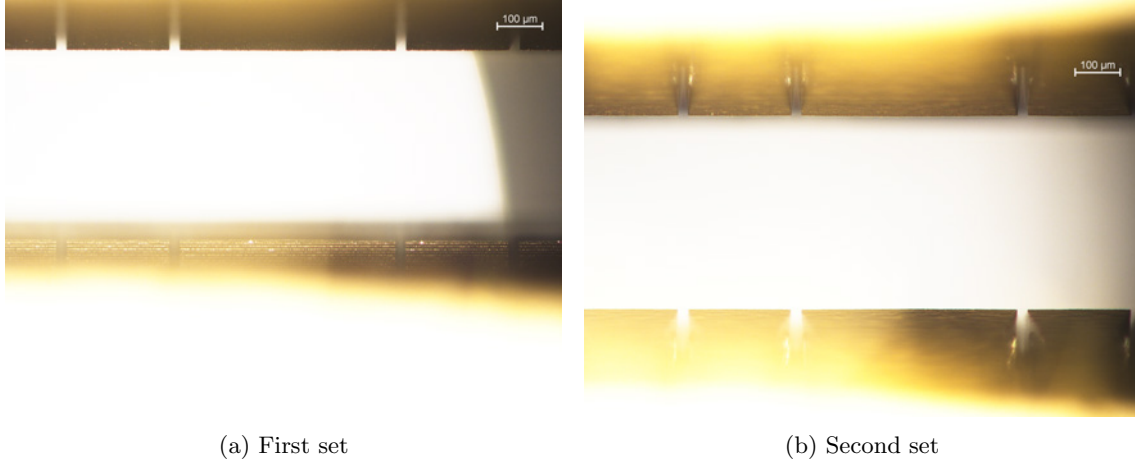


Figure C.23: Electrodes of Trap nb. 1. After evaporation coating of 100 nm titanium and 200 nm gold on top. The coating has been process after piranha cleaning of the part. Objective 10x.

Recto

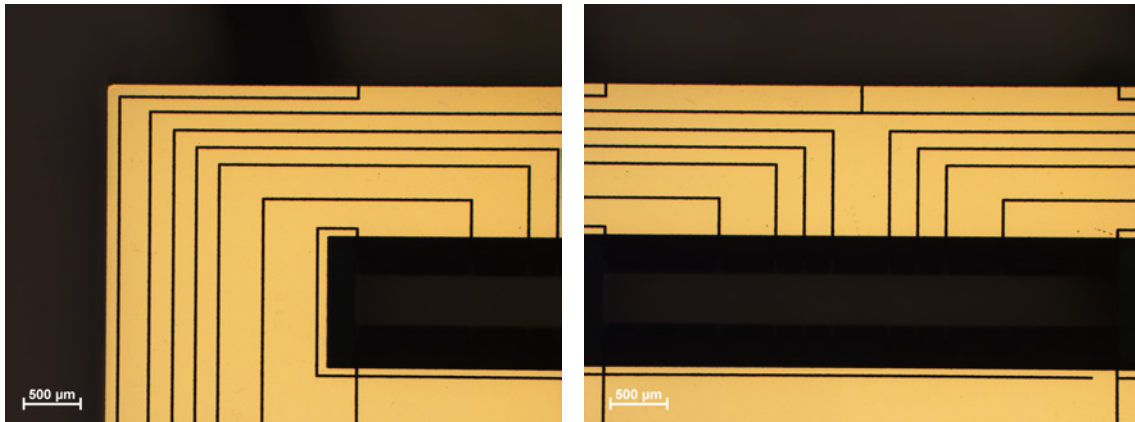


Figure C.24: Trap nb. 1 features inspection (recto). After evaporation coating of 100 nm titanium and 200 nm gold on top. The coating has been process after piranha cleaning of the part. Objective 2.5x.

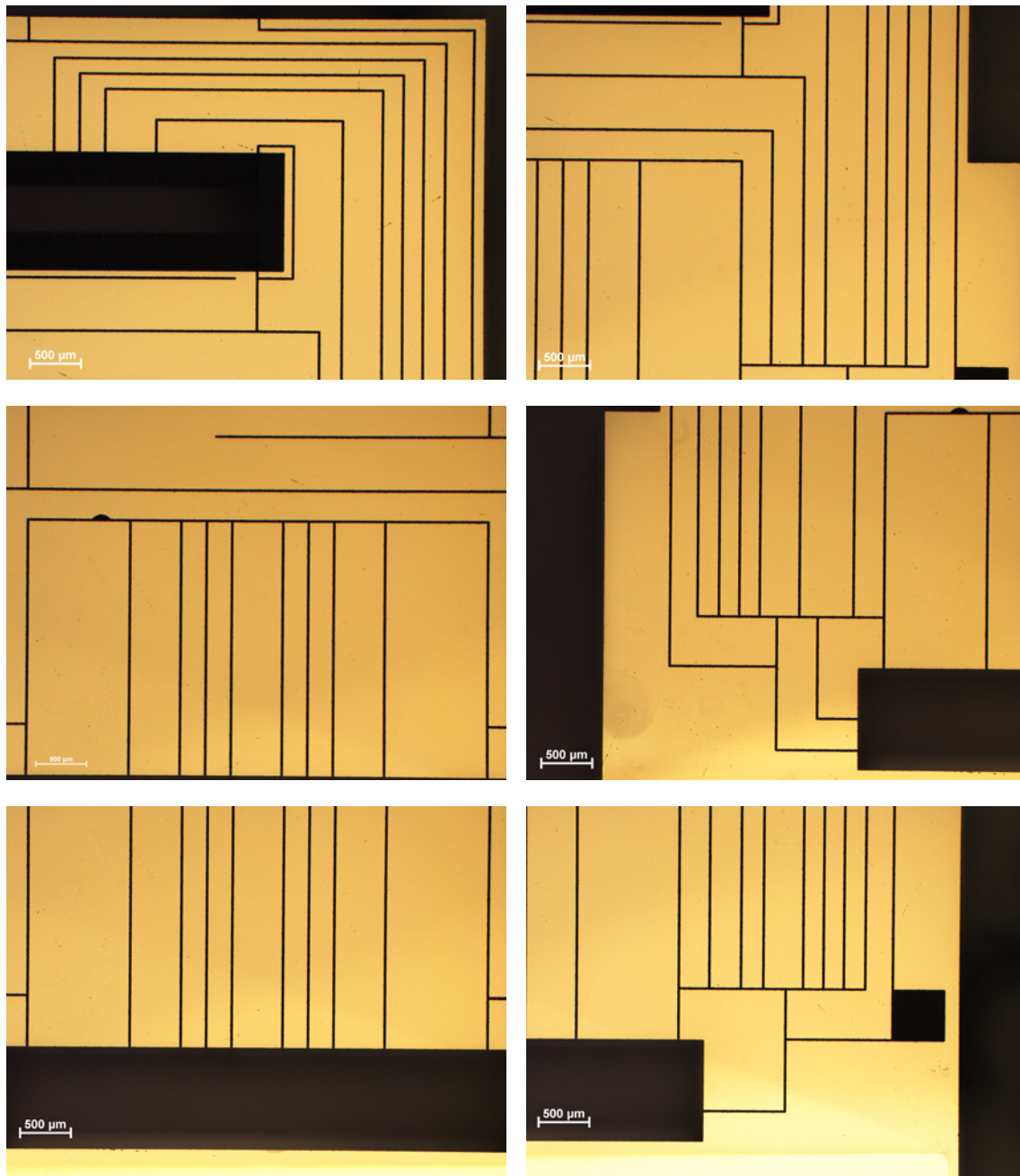


Figure C.25: Trap nb. 1 features inspection (recto). After evaporation coating of 100 nm titanium and 200 nm gold on top. The coating has been process after piranha cleaning of the part. Objective 2.5x.

Verso

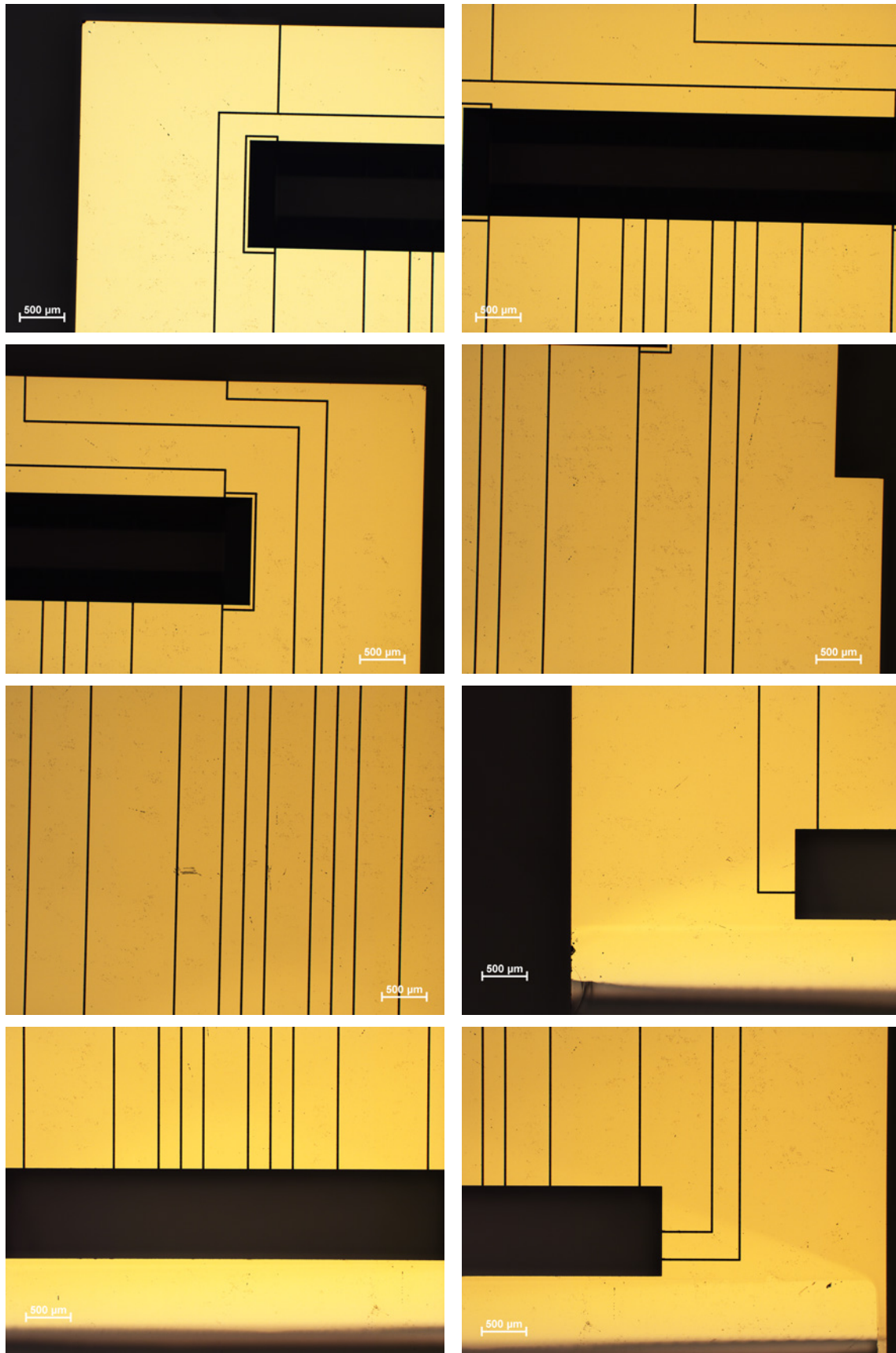


Figure C.26: Trap nb. 1 features inspection (verso). After evaporation coating of 100 nm titanium and 200 nm gold on top. The coating has been process after piranha cleaning of the part. Objective 2.5x.

Defect

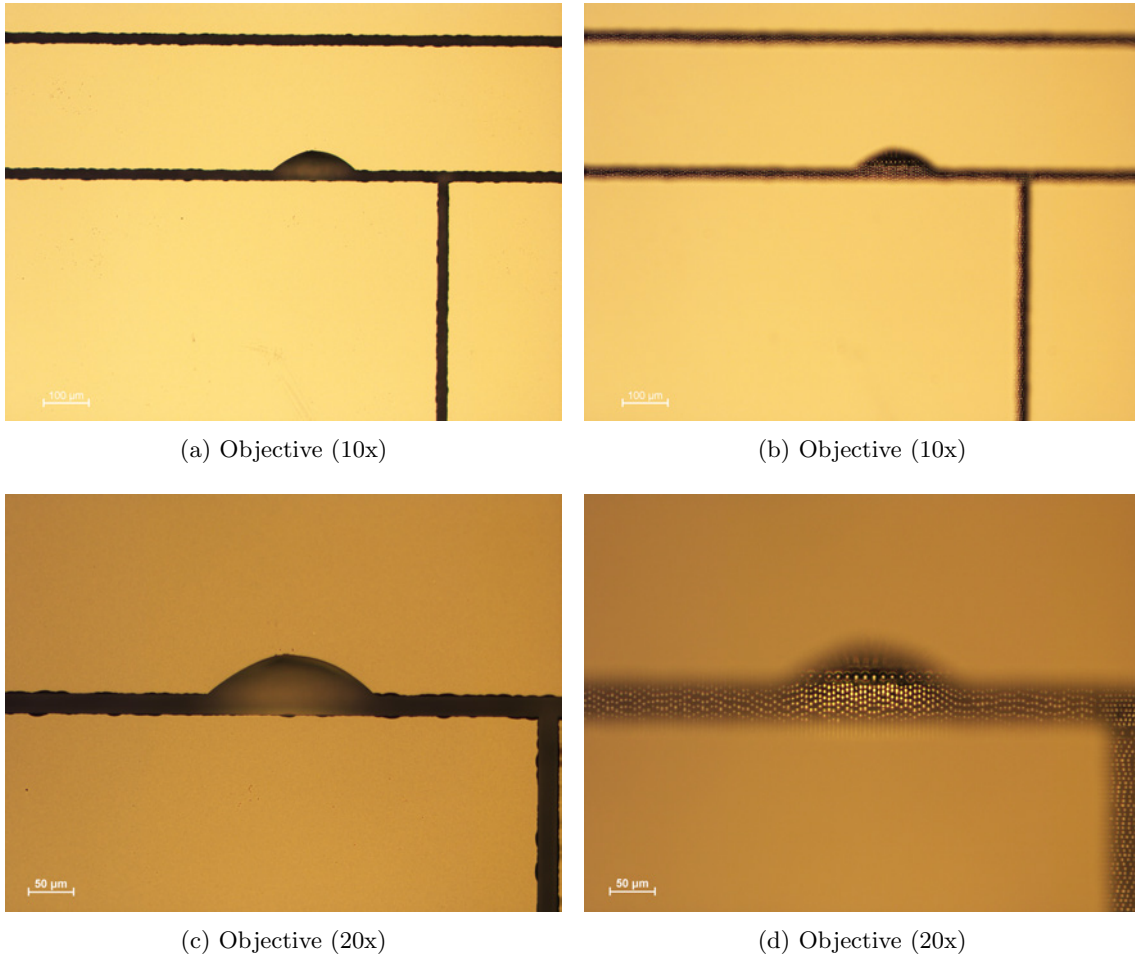


Figure C.27: Trap nb. 1 defect inspection after evaporation. The focus on the left pictures is on the surface of the trap. The focus on right pictures is on the bottom of the trenches.

Trap 2

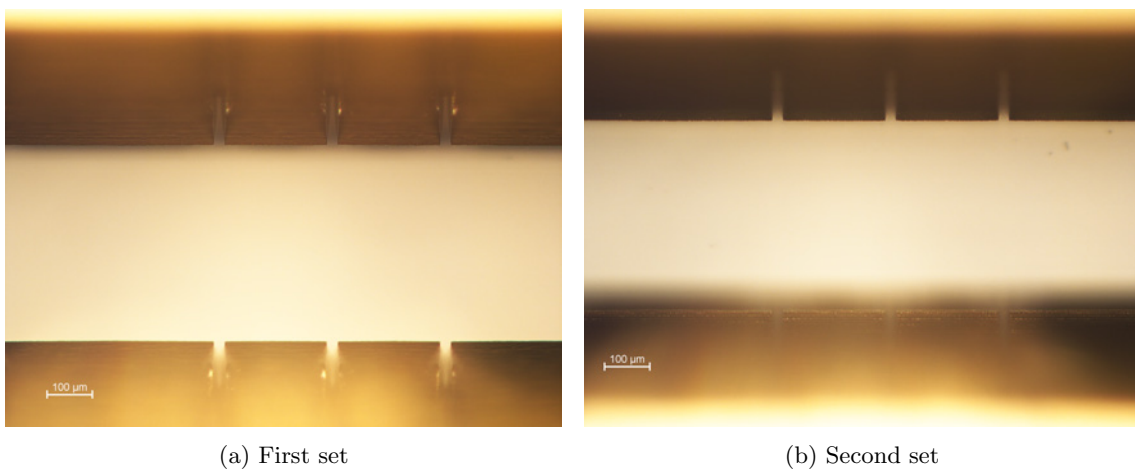


Figure C.28: Electrodes of Trap nb. 2. After evaporation coating of 100 nm titanium and 200 nm gold on top. The coating has been process after piranha cleaning of the part. Objective 10x.

Recto

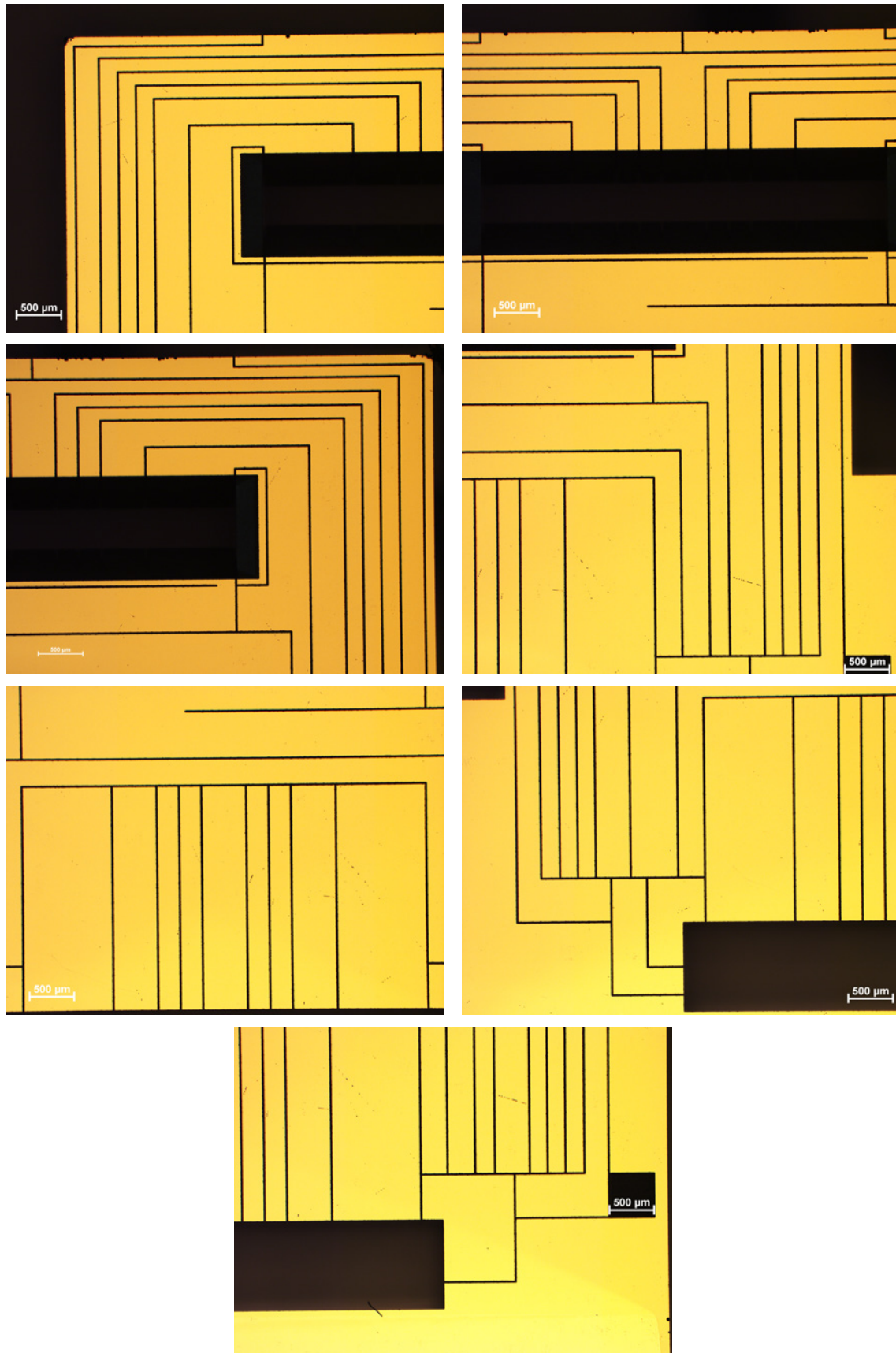


Figure C.29: Trap nb. 2 features inspection (recto). After evaporation coating of 100 nm titanium and 200 nm gold on top. The coating has been process after piranha cleaning of the part. Objective 2.5x.

Verso

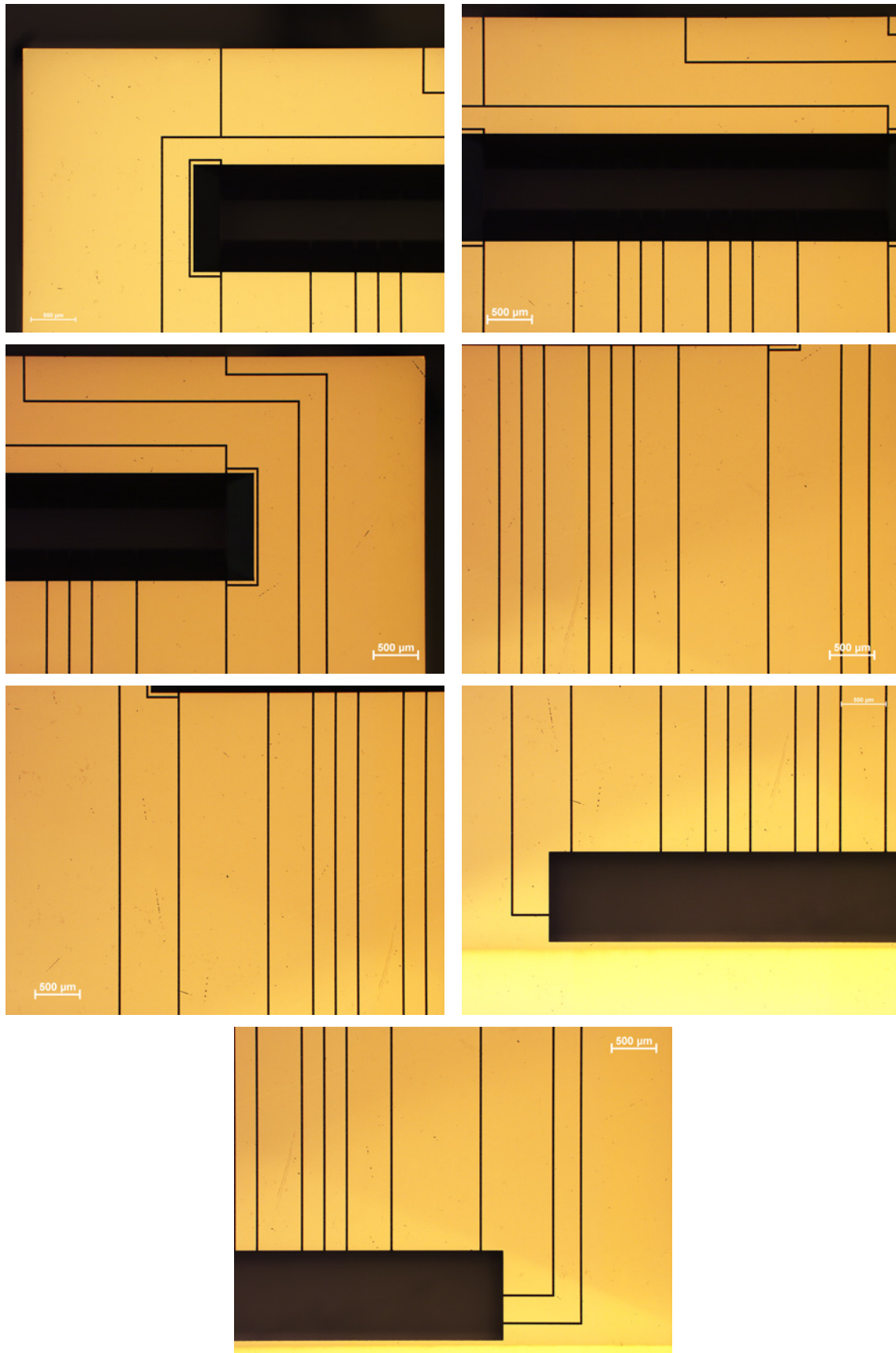


Figure C.30: Trap nb.2 features inspection (verso). After evaporation coating of 100 nm titanium and 200 nm gold on top. The coating has been process after piranha cleaning of the part. Objective 2.5x.

C.2.2 Scanning Electron Microscopy pictures

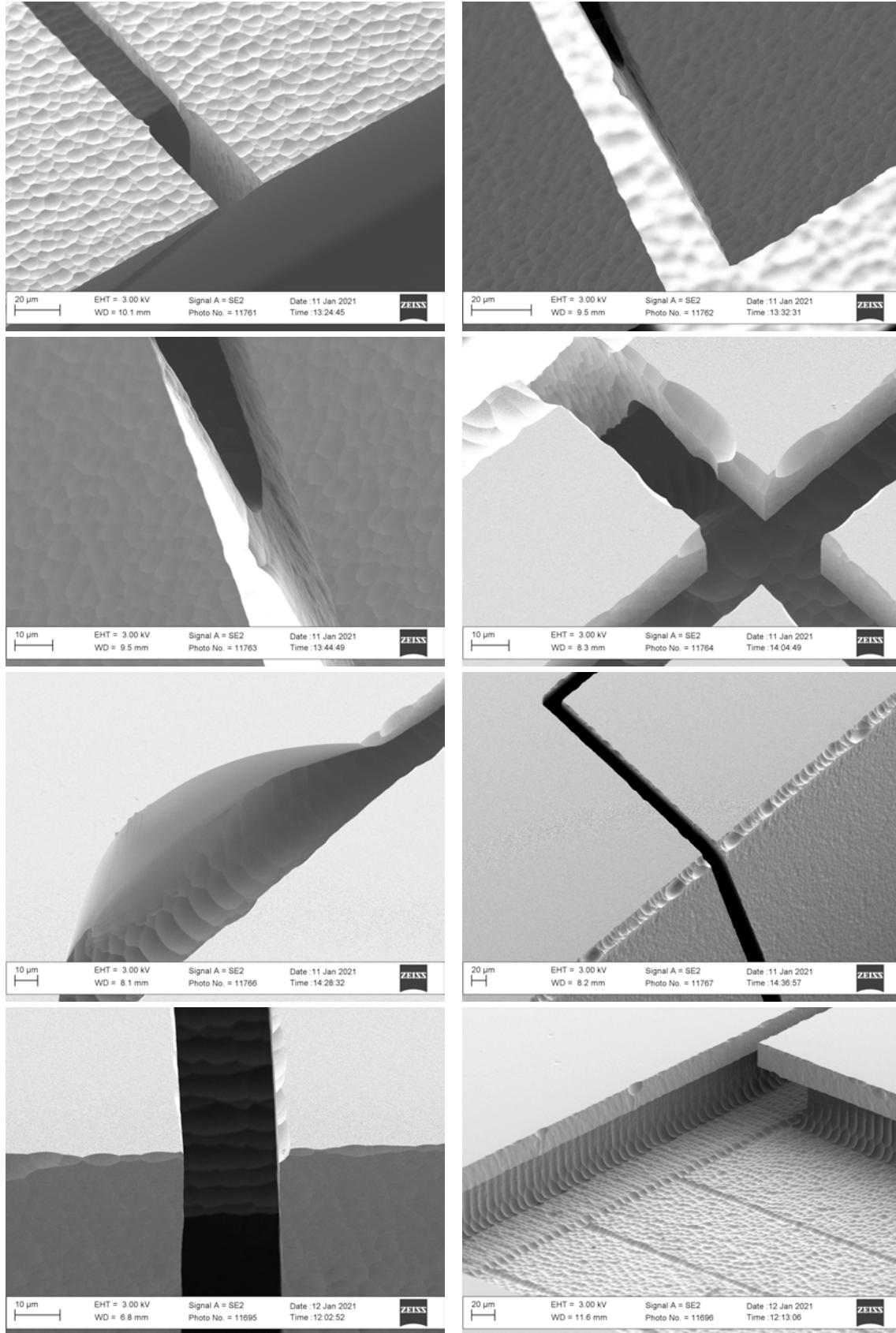


Figure C.31: Scanning Electron Microscopy (SEM) pictures of the trap nb. 1. After evaporation coating of 100 nm titanium and 200 nm gold on top.

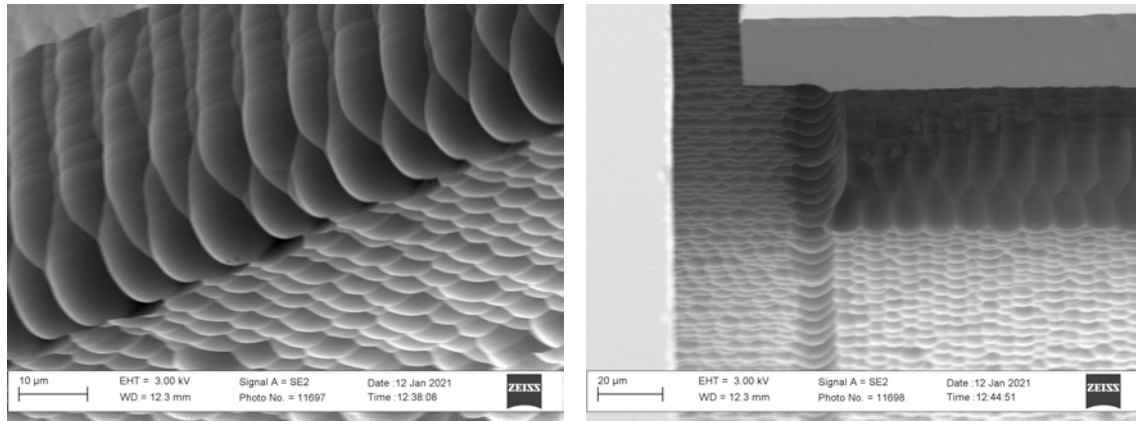


Figure C.32: Scanning Electron Microscopy (SEM) pictures of the trap nb. 1. After evaporation coating of 100 nm titanium and 200 nm gold on top.

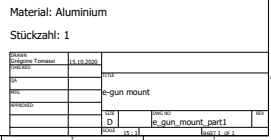


Figure D.2: Electron gun mount. Drawing of part 1.

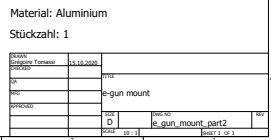
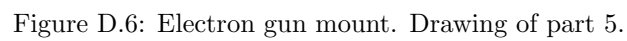


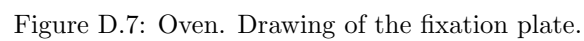
Figure D.3: Electron gun mount. Drawing of part 2.

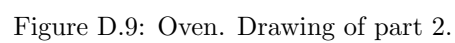
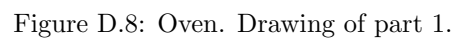
Figure D.4: Electron gun mount. Drawing of part 3.

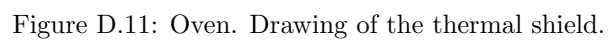
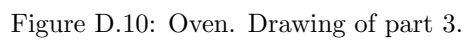
Figure D.5: Electron gun mount. Drawing of part 4.



D.2 Oven







D.3 Trap holder

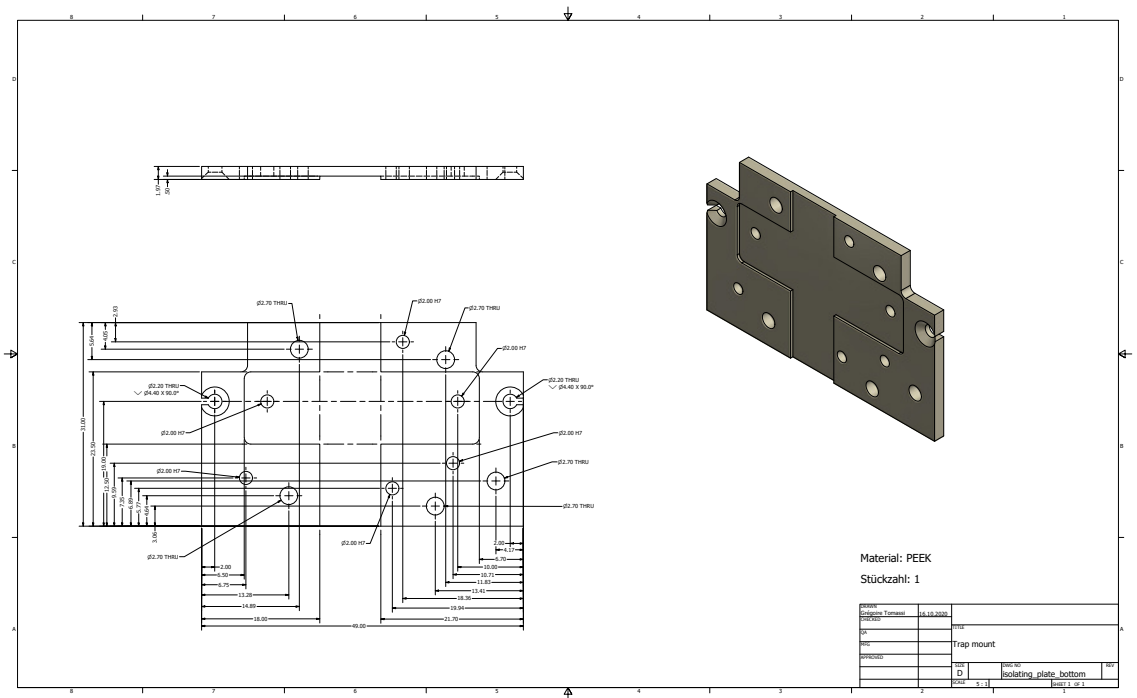


Figure D.12: Trap holder. Drawing of the fixation plate.

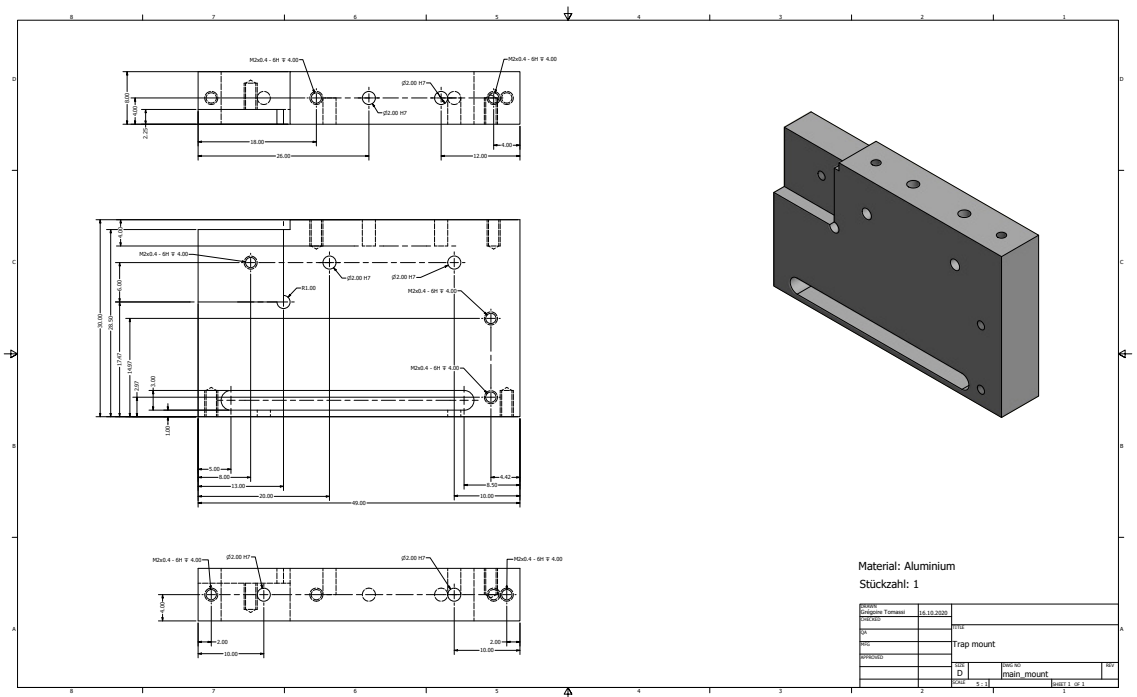


Figure D.13: Trap holder. Drawing of part 1.

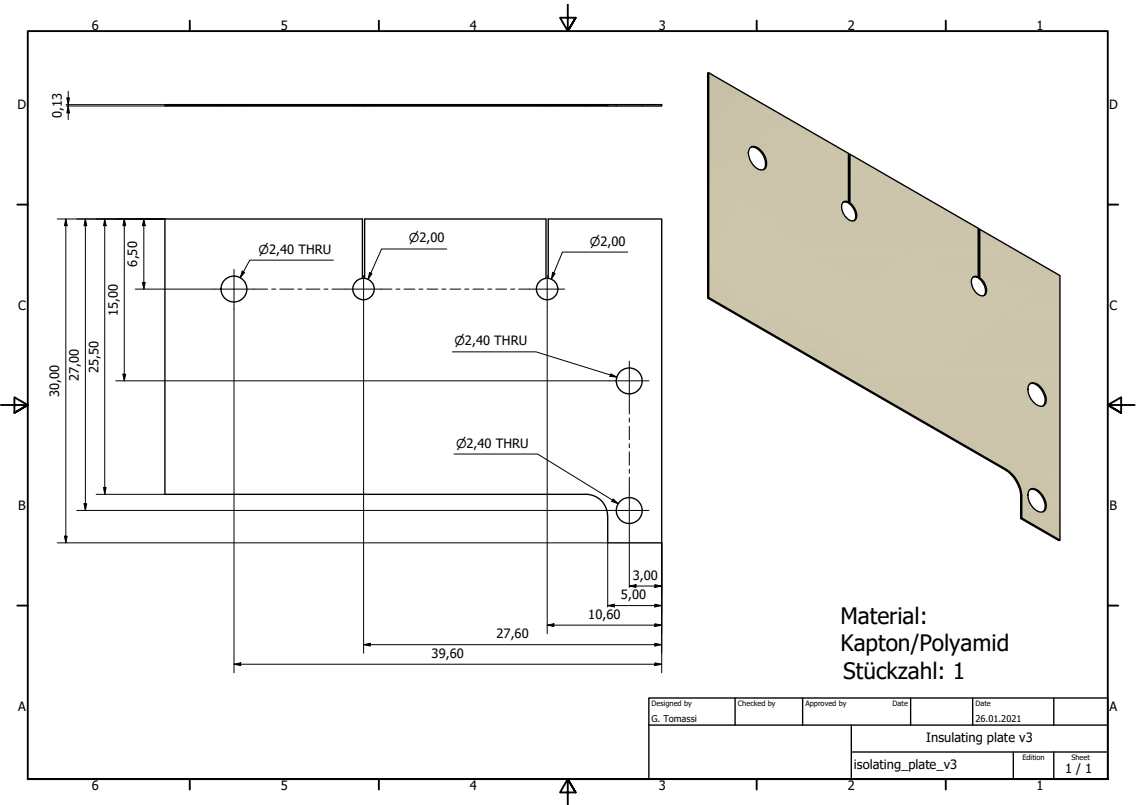


Figure D.14: Trap holder. Drawing of part 2.

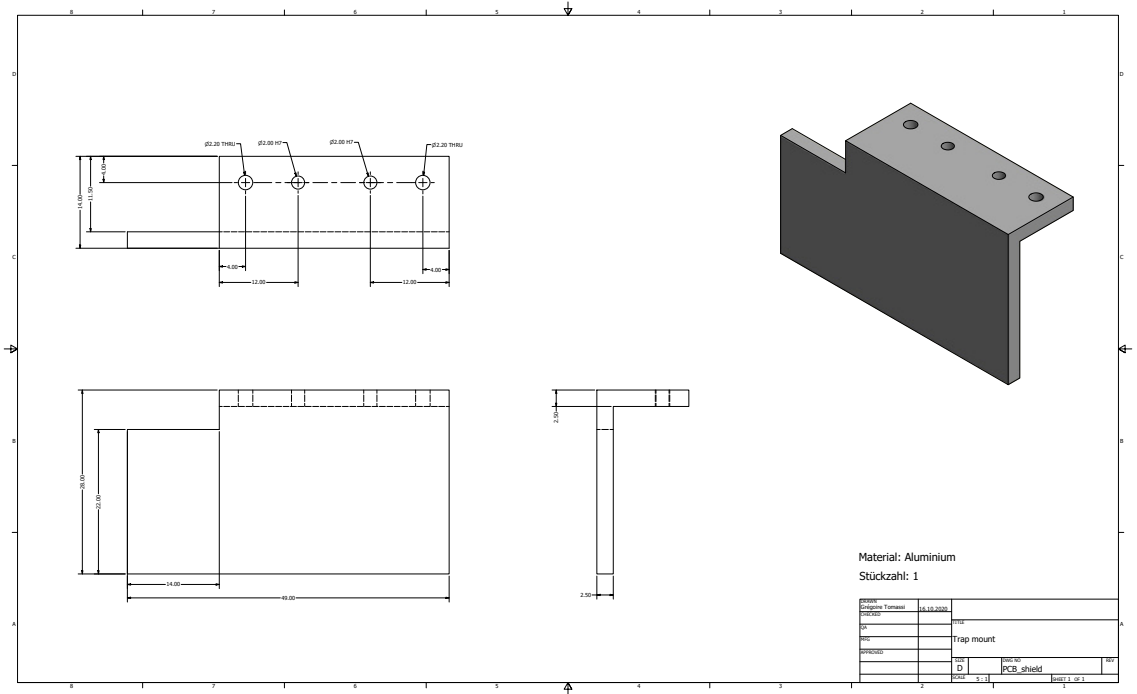


Figure D.15: Trap holder. Drawing of part 3.

D.4 Evaporation holder

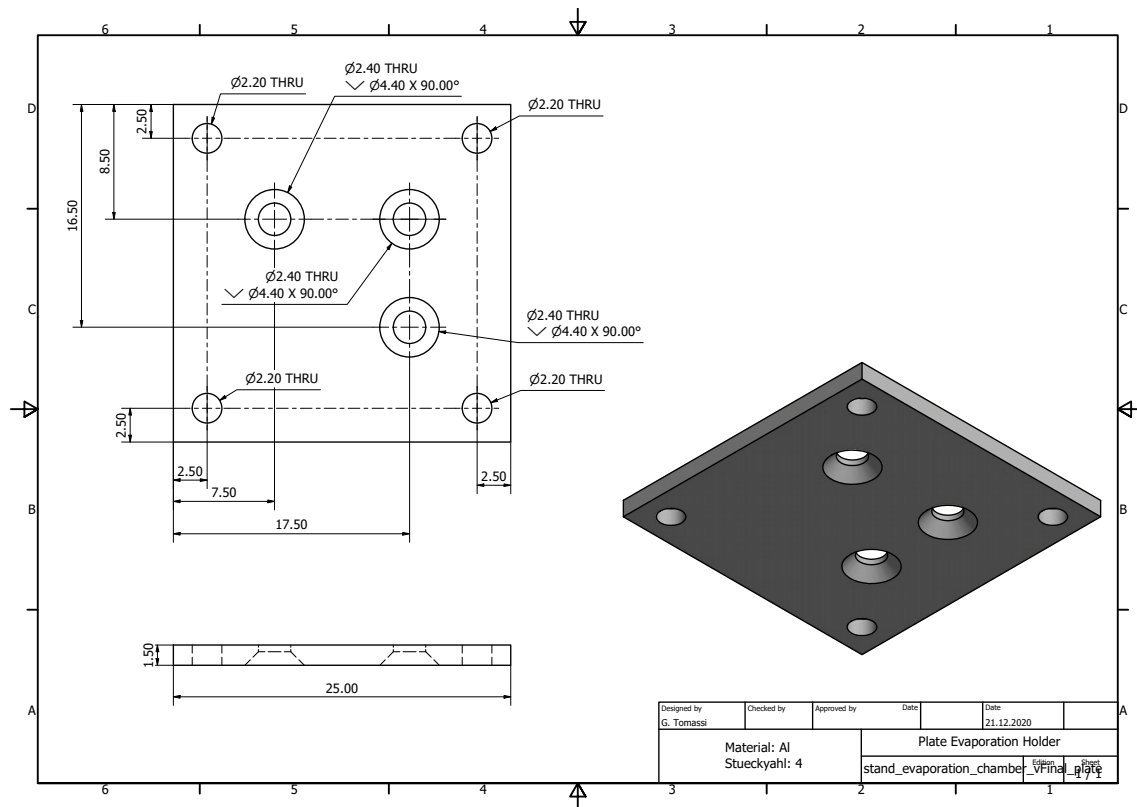


Figure D.16: Trap evaporation holder. Drawing of the fixation plate.

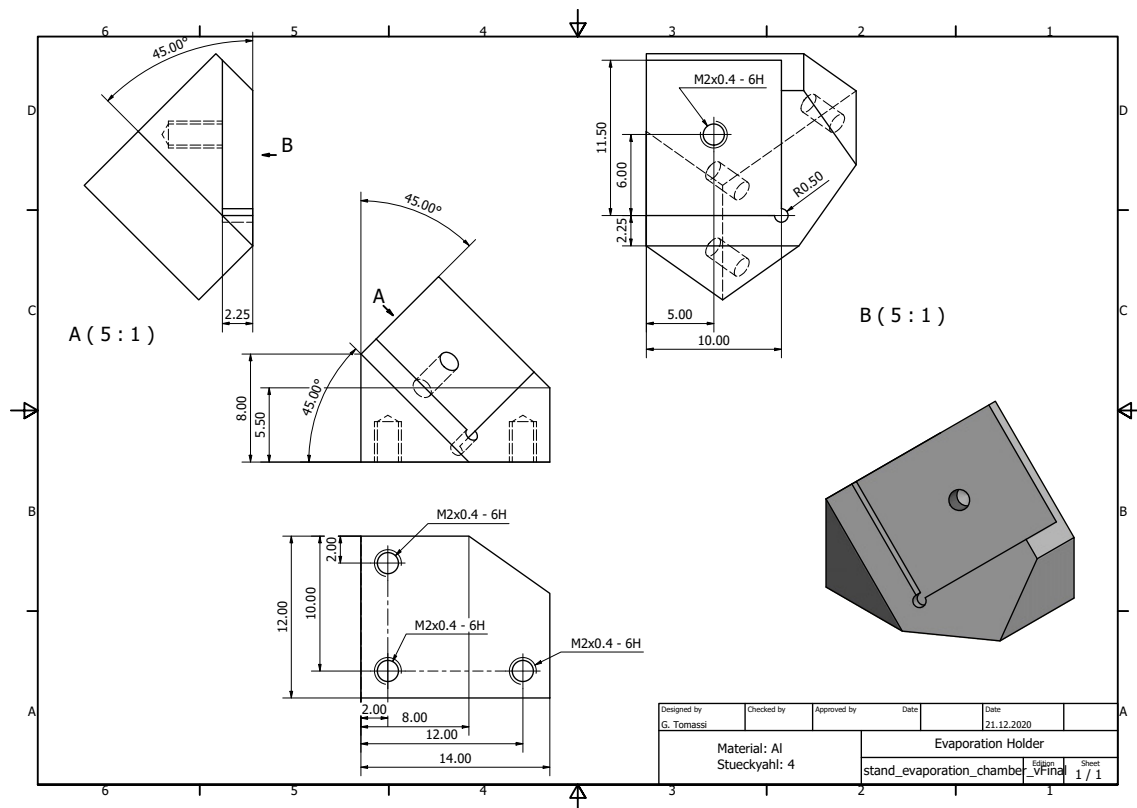


Figure D.17: Trap evaporation holder. Drawing of part 1.

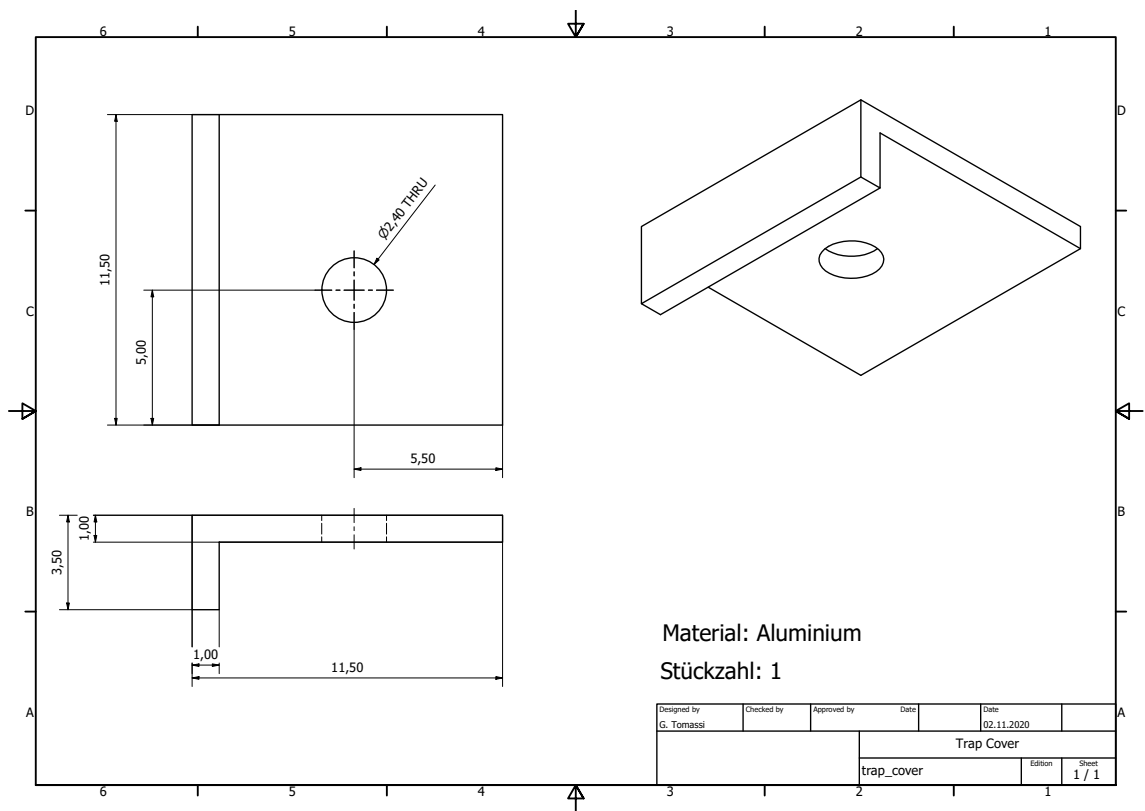


Figure D.18: Trap evaporation holder. Drawing of part 2.