Final Project Report

ME4310

Micro/Nano Electro-Mechanical Systems and Nanotechnology

Design and Simulation of MEMS based Thermally actuated Microgripper with Active Release Mechanism

By

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07th November *2023*

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1 Introduction

1.1 Micro Electro-Mechanical Systems (MEMS)

Micro Electro-Mechanical Systems (MEMS) are little integrated apparatus or arrangement that integrates electrical and mechanical elements. They vary in size from the sub micrometre altitude to the millimetre altitude and there can be several numbers, from a small number to millions, in a specific system. MEMS broaden the fabrication approaches developed for the integrated circuit industry to include mechanical elements for instance beams, gears, diaphragms, and springs to devices.

These devices can sense, manage and trigger the mechanical processes on the micro scale, and perform independently or in arrays to produce effects on the macro scale. The micro fabrication machinery facilitates fabrication of huge arrays of apparatuses, which independently carry out simple tasks, but in combination can carry out complicated functions. The major applications MEMS device comprises of fluid pumps, inkjet-printer, cartridges, micro-engines, locks, inertial sensors, micro-transmissions, micro-mirrors, micro actuators, optical scanners, miniature robots, accelerometers, transducers and chemical, pressure and flow sensors. Latest applications are budding as the existing application is applied to the miniaturization and combination of traditional devices.

1.2 MEMS based Microgrippers

MEMS-based microgrippers are miniature devices that use microelectromechanical systems (MEMS) technology to grasp and manipulate objects at the microscopic level. They are typically fabricated on silicon wafers using standard microfabrication techniques, such as photolithography, etching, and deposition.

MEMS-based microgrippers have a wide range of applications, including but not limited to Micro-assembly, Micromanufacturing, Micromanipulation. Micro-assembly deals with the assembling of microelectronic devices and other small components while micromanufacturing deals with manipulating materials and devices during manufacturing processes. An upcoming area of research has been in the biomedical area in manipulating cells and tissues for research and medical applications.

MEMS-based microgrippers can be actuated using a variety of methods, including thermal, electrostatic, piezoelectric, Shape Memory Alloys, etc. MEMS-based microgrippers offer several advantages over traditional microgrippers. MEMS-based microgrippers can be incredibly small, making them ideal for manipulating objects at the microscopic level. They also can be very precise, allowing them to manipulate objects with great accuracy.

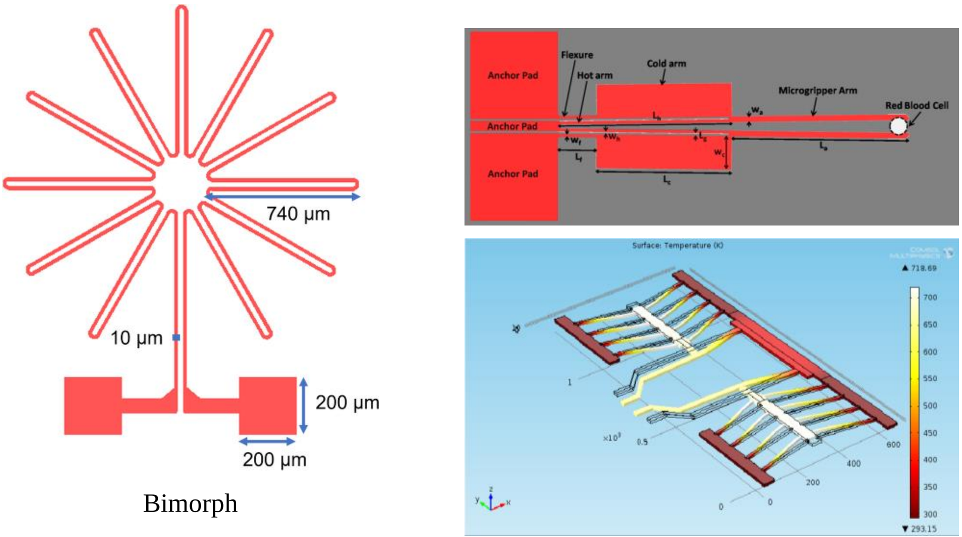
As MEMS technology continues to develop, MEMS-based microgrippers are becoming increasingly sophisticated and versatile. They are now being used in a wide range of applications, and their potential impact on a variety of industries is still being explored.

1.3 Electrothermal Microgrippers

Electrothermal actuators are driven by the Joule heating effect and subsequent differential thermal expansion. They encompass three primary categories: hot-and-cold arm actuation (U-shaped actuators), chevron actuators (V-shaped actuators), and bi-morph actuators. Figure 3-1 shows the types of electrothermal microgrippers.

A notable disadvantage of conventional hot-and-cold-arm micro actuators lies in the fact that both the flexure and the cold arm are integral parts of the electrical circuit, meaning that only a fraction of the applied power contributes to the actuator's deflection. Moreover, the integration of the flexure into the electrical loop hinders its scalability.

Chevron electrothermal actuators have emerged as an alternative solution, often incorporating a compliant amplification mechanism to amplify their motion range. This approach effectively addresses the shortcomings of hot-and-cold arm actuators.[1]



U-shaped
(Hot-arm Cold-arm)

V-shaped
(Chevron Shaped)

Figure 1-1 Types of electrothermal microgrippers.[1]

1.4 Parameters of Microgripper Design

The successful manipulation of micro-objects with fragile structures and accurate placement at their final destination hinges on the meticulous design of the microgripper. This intricate process requires a thorough understanding of the factors that influence gripper performance, enabling the development of high-performance structures with minimal operational errors. These parameters may include material Specification, displacement amplification factor, parallel and rotational motion of jaws, gripping range and stroke, normally open and normally closed gripper, out of plane motion, simultaneous motion of jaw, Number of degrees of freedom, shape of tips, and release mechanism. The table 1-1 summarizes these parameters.

Table 1 Effective Parameters of Microgripper Design [2]

Parameter	Description
Material specification	The type of material used in the gripper, such as silicon, aluminum alloy, or stainless steel.
Displacement amplification factor	The ratio between the output displacement (jaw displacement) and the input displacement applied from the micro actuator to the gripper mechanism.
Gripping range and stroke	The gripping range is the maximum and minimum diameter of objects gripped by the microgripper. The gripping stroke is the maximum stroke of each jaw.
Parallel motion of jaws	Whether the gripper jaws move in parallel or in a rotational motion. Parallel motion is more precise and reliable.
Normally open and normally closed gripper	Whether the gripper is normally open (the gap is maximum, and the force is applied to decrease the gap) or normally closed (the gap is increased to the object dimension domain by the force, and the object is grasped).
Out of plane motion of gripper	Whether the gripper arms move in the same plane during the grasping and releasing process. Out of plane motion reduces gripper efficiency.
Simultaneous motion of gripper jaw	Whether both gripper jaws move simultaneously to grip the object, or only one jaw moves.
Ideal shape of tips	The shape of the gripper tips, such as flat, sawtooth, or micro pyramids.

Number of degrees of freedom	Whether the gripper has one degree of freedom (both jaws move together), two degrees of freedom (each jaw moves independently), or three degrees of freedom.
Releasing the objects from tips	The method used to release the object from the gripper tips, such as passive (using material with low adhesion potential, decreasing the contact area, etc.) or active (applying an electric field, vibration, vacuum suction, or freezing/thawing of ice droplets).

1.5 Microgripper Release Mechanisms

One of the persistent challenges in micromanipulation is the release of micro-objects from the end effector due to the prevalence of strong adhesion forces at the microscale. This phenomenon arises from force scaling, where surface forces, such as adhesion forces, including capillary force, electrostatic force, and van der Waals force, become significantly stronger than volumetric forces, such as gravity, at the microscale. As a result, objects at the microscale tend to adhere strongly to the end effector, making their release a delicate and challenging task.

The dominance of surface forces at the microscale can be attributed to the inverse relationship between force and the characteristic length scale. As the size of objects decreases, the surface area-to-volume ratio increases, leading to a proportional increase in surface forces. In contrast, volumetric forces, such as gravity, remain relatively constant. This disparity in force magnitudes results in the strong adhesion of micro-objects to the end effector, particularly during the release process.

Several factors contribute to the strong adhesion forces at the microscale:

Capillary Force: Capillary force arises from the interaction of surface tension and the meniscus formed between the object and the end effector. This force tends to increase with decreasing object size and can significantly hinder release.

Electrostatic Force: Electrostatic forces arise from the attraction or repulsion between charged surfaces. At the microscale, even small electrostatic charges can exert significant forces, making release particularly challenging for charged objects.

van der Waals Force: van der Waals force is a weak but ubiquitous force that originates from the interaction of fluctuating dipole moments between molecules. While relatively weak at larger scales, van der Waals force becomes increasingly significant at the microscale, contributing to the strong adhesion of objects.

Overcoming these strong adhesion forces and achieving reliable release of micro-objects is crucial for successful micromanipulation. Incorporating active release mechanisms into end effectors provides a more controlled approach to releasing micro-objects. These mechanisms can utilize various principles, such as thermal expansion, piezoelectric actuation, or shape memory alloys, to actively disengage the object from the end effector.

2 Motivation

Thermally actuated microgrippers, which utilize heat to induce shape changes and gripping actions, offer several advantages over other actuation methods. They are simple in design, easy to fabricate, and compatible with various heat sources. However, conventional thermally actuated microgrippers often face challenges in releasing the grasped object due to inherent constraints in their design.

The incorporation of an active release mechanism into a thermally actuated microgripper addresses this limitation by providing a controlled and reliable release operation. This mechanism enables the microgripper to release the object without requiring external forces, minimizing the risk of damaging delicate microstructures or cells. In particular, the active release mechanism offers distinct advantages for applications in biomedical research, where the integrity of delicate biological samples is paramount. The ability to gently release cells or tissues without applying external forces minimizes the risk of damage and contamination, ensuring the preservation of sample integrity for subsequent analysis or experimentation.

Incorporation of an active release mechanism into thermally actuated microgrippers provides a powerful tool for biomedical research, enabling delicate manipulation and release of biological samples without compromising their integrity. This technology holds the potential to revolutionize various biomedical applications, including cell manipulation, tissue engineering, and diagnostic testing.

3 Literature Review

3.1 Thermoelectrically actuated microgrippers

Surface-micromachined thermal actuators harness the principle of constrained thermal expansion to generate amplified motion. This actuation mechanism typically employs Joule heating, where an electric current passing through thin actuator beams induces heat generation. Two prevalent thermal actuator designs, the pseudo-bimorph or "U"-shaped actuator and the bent-beam or "V"-shaped actuator, have been extensively studied and implemented.

Both designs amplify the minute input displacement caused by thermal expansion, albeit at the cost of reduced output force. The U-shaped actuator, depicted in Figure 3-1, operates by establishing a temperature differential between a hot-arm and cold-arm segment. This temperature difference stems from the diminished Joule heating in the cold arm due to its decreased electrical resistance, which arises from its larger cross-sectional area. Consequently, a thermal expansion disparity between the two segments emerges. As both segments are anchored at their base, the actuator end undergoes a rotary motion. By connecting multiple actuators in parallel, both output force can be augmented, and linear output motion can be achieved.

In contrast, the V-shaped or chevron-style actuator, illustrated in Figure 3-2, features one or more V-shaped beams, often referred to as legs, arranged in parallel. When current traverses these beams, they heat up and expand. Due to the shallow angle of the beams, the central shuttle experiences amplified displacement in the direction of the offset. [3]

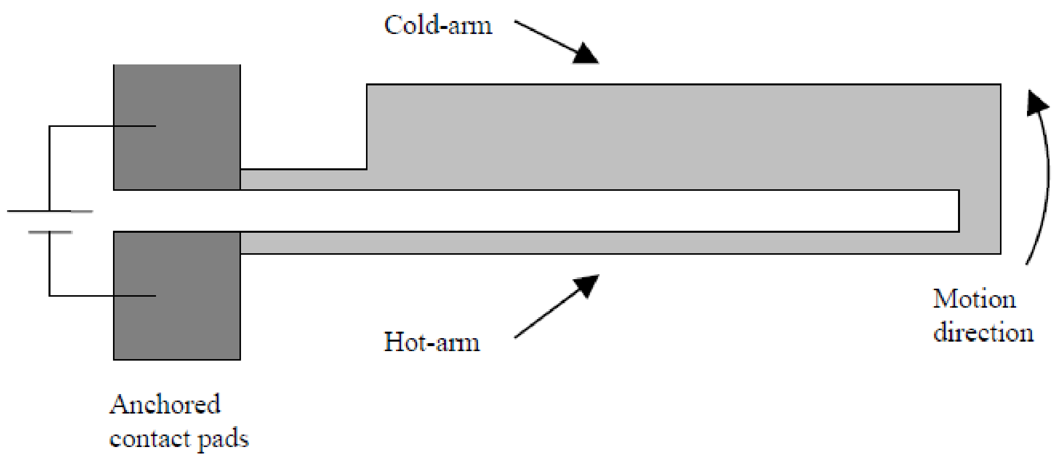


Figure 3-1 U-shaped or Pseudo bimorph actuator design [2]

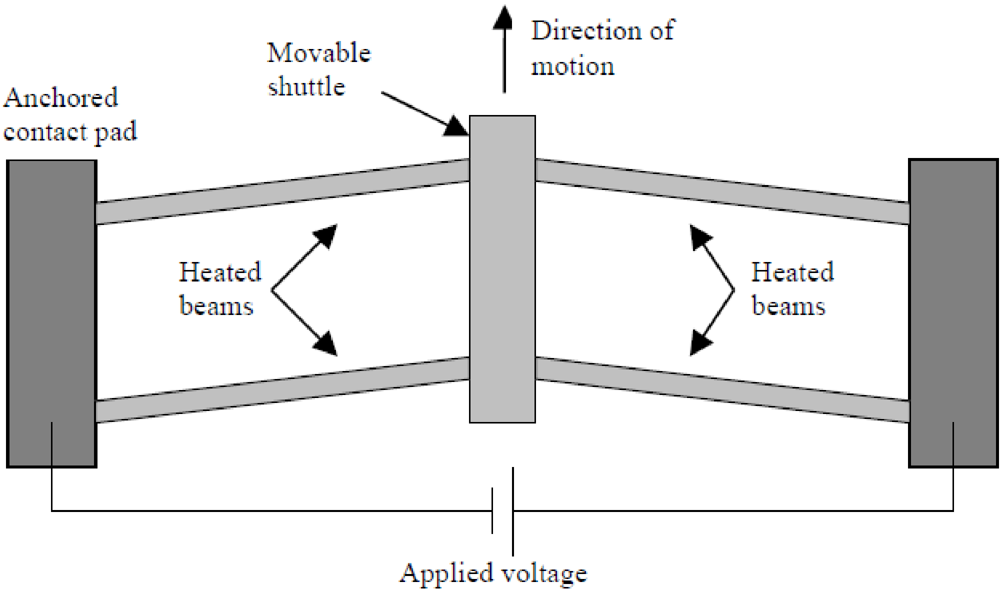


Figure 3-2 V-shaped or chevron-shaped actuator design [2]

3.2 Microgripper Release Mechanisms

3.2.1 Passive Release Mechanisms

Table 2 Summary of Passive Release Mechanisms

Method	Description
Material selection	Use materials with low adhesion potential to the gripped object.
Contact area reduction	Minimize the contact area between the gripper tips and the object to reduce adhesion forces. Rough surfaces can aid in reducing contact area.
Material hardness	Opting for hard materials in gripper fabrication to minimize deformation and prevent an increase in contact area and adhesion forces during gripping.
Tension force reduction	Employ dry atmospheres or hydrophobic coating methods to decrease capillary forces (tension forces).
Tension force utilization	Enhance adhesion between the object and the substrate to facilitate object release.

3.2.2 Active Release Mechanisms

Table 3 Summary of Active Release Mechanisms

Method	Description
Electric field	An electric field is created between the probe and the substrate to detach the object from the probe. Requires conductive micro object, probe, and substrate.
Mechanical vibration	Mechanical vibration is used to detach the objects from the tips. Requires a large bandwidth of the manipulator.
Vacuum suction	Vacuum-based tools are used to create a pressure difference for pick and release. Limited to vacuum environments.
Freezing/thawing of ice droplets	Micro Peltier coolers are used to form ice droplets instantaneously for picking–placing of micro-objects. The thawing of the ice droplets is used to release the objects. Requires a bulky complex end effector and is limited to micromanipulation in an aqueous environment.
Plunger arm	A plunger arm pushes out the object out of the gripper jaws in the releasing process.

3.2.3 Plunger Release Mechanism

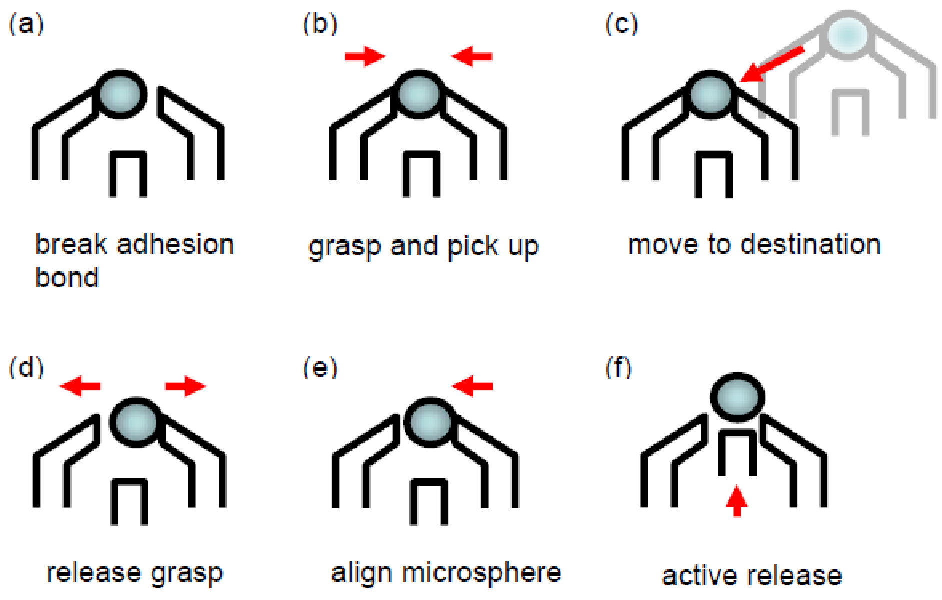


Figure 3-3 Steps of Plunger Release Mechanism [4]

4 Proposed Design and Working Principle

This microgripper design utilizes V-shaped/Chevron-shaped electro-thermal actuators to control its grasping and releasing actions. Composed of two arms that open upon actuation to capture micro-objects, the microgripper exhibits an initial opening of 10 micrometers. Simulations conducted using COMSOL Multiphysics 5.3a software demonstrate the structure's effectiveness when actuated in an air environment.

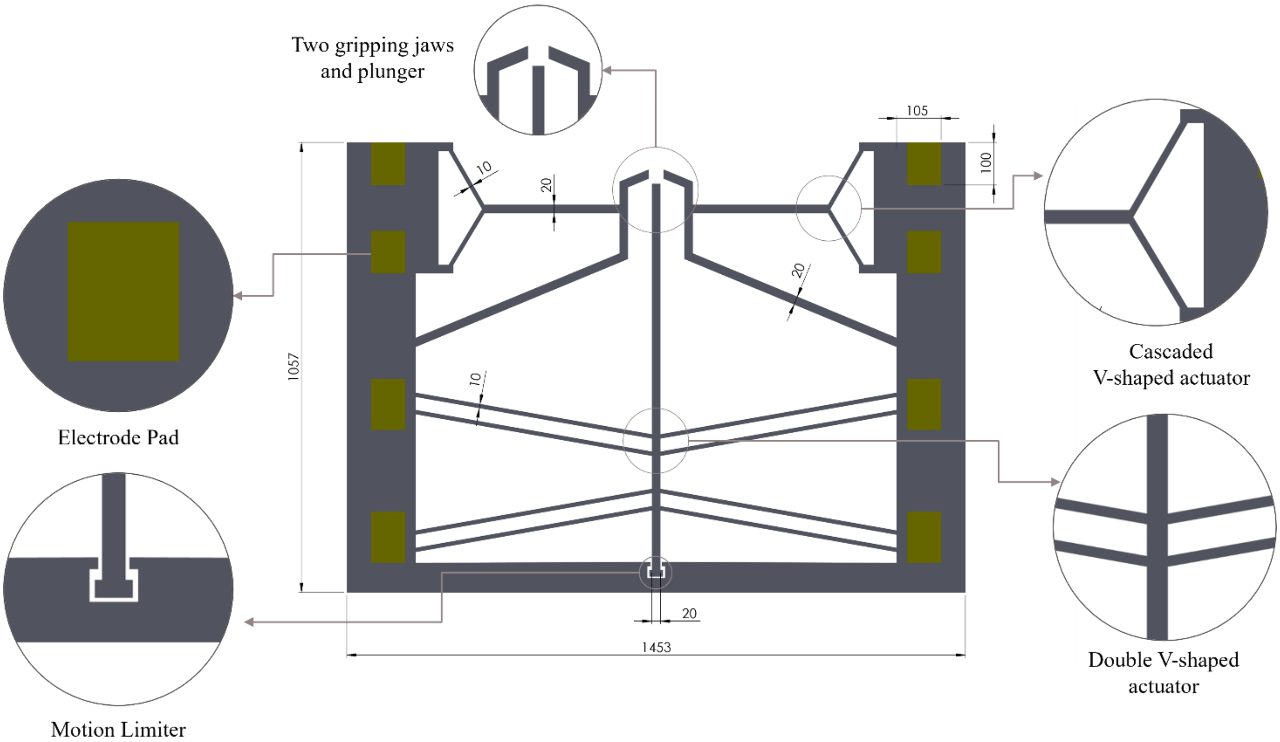


Figure 4-1 Structural dimensions and salient features

The working principle of the proposed design can be attributed to Joule Heating and Thermal Expansion. Then the actuation can be studied under the Gripping Mechanism and the Releasing Mechanism.

Here the Joule Heating effect takes place by the electrical current that is applied to the metallic microheaters embedded within the gripper arms. This current flow causes resistance in the microheaters, leading to Joule heating, which converts electrical energy into thermal energy. Thus, the temperature of the microheaters increases as the electrical current increases.

Due to their high coefficient of thermal expansion, the heated microheaters expand significantly compared to the surrounding SU-8 polymer. This expansion creates a stress gradient in the gripper arms, causing them to bend outward in a "V" or chevron shape.

As the gripper arms bend outward, the gap between the gripper tips widens. This allows the microgripper to grasp and hold objects placed between the tips. The size of the object that can be grasped depends on the maximum displacement of the gripper arms, which is determined by the design and material properties of the microgripper.

To release the grasped object, the electrical current is stopped or reduced. This allows the microheaters to cool down and contract back to their original size. As the gripper arms contract, the gap between the tips closes, releasing the object.

5 Material Selection

Silicon-based thermally actuated microgrippers face several challenges for biological applications. High operating temperatures during actuation can potentially harm delicate biological samples. Electrical conductivity of the silicon material poses a risk of electrical interference with biological processes. The high Young's modulus of silicon can lead to excessive gripping forces that may damage biological cells.

Despite the promise of Si-polymer composites in addressing these limitations, the complexity of fabrication processes could potentially negate some of the anticipated advantages.

Polymer fabrication offers several advantages over silicon micromachining, particularly in terms of cost and versatility. Polymers are inherently more cost-effective due to their lower bulk material prices and ease of processing, enabling faster production cycles. Moreover, the increasing demand for disposable devices in biological and medical applications necessitates the use of inexpensive materials and fabrication processes.

The microgrippers were constructed using SU-8 biocompatible polymer as the structural material. This choice of material makes the microgrippers suitable for bio-micromanipulation and micro assembly applications [4]. Being mechanically and thermally stable, resistant to most organic solvents and acids, compatible with standard Si processing & most analytical chemicals and the ability to be functionalized for biological applications due to its unreacted epoxy groups make SU-8 a favourable choice for this application.

In addition, since SU8 can act as an adhesion layer for the gold metallization and encapsulate the microgripper's resistors it further suits the requirements.

Metallic microheaters are embedded within the polymeric structural layers of the microgrippers to prevent electrical contact with the manipulated object, enhance thermal efficiency, and minimize unwanted out-of-plane displacement of the gripper tips. Gold (Au) was chosen as the metallic material due to its high biocompatibility, low Young's modulus, high coefficient of expansion compared to other metals, ductility and reasonably good adhesion to SU-8 without the need for adhesion promoters.

The material properties of the materials in use are found in Figure 5-1.

Material properties FEA	SU8	Au	Air
E [MPa]	$4.4 * 10^3$	$5.7 * 10^4$	-
Poisson	0.22	0.35	-
TCE [1/K]	$5.2 * 10^{-5}$	$1.2 * 10^{-6}$	-
κ [pW/ µm K]	$2 * 10^5$	$297 * 10^5$	-
σ_0 [pS/ µm]$^{(*)}$	-	$5.022 * 10^{13}$	-
κ_0 [W/ m K]$^{(**)}$	-	-	0.025642

$^{(*)}$ $4*10^{-11}\,T^4 - 1*10^{-7}\,T^3 + 1*10^{-4}\,T^2 - 0.0647\,T + 16.011$

$^{(**)}$ $72 * 10^{-6} + 0.025642\,T$

Figure 5-1 Material Properties [5]

6 Fabrication process

The fabrication process is followed to deposit an SU-8 layer of 1.5 um thickness first then a comparatively thinner layer of Au of 300 nm thickness followed by another layer of SU-8 of 1.5 um thickness.

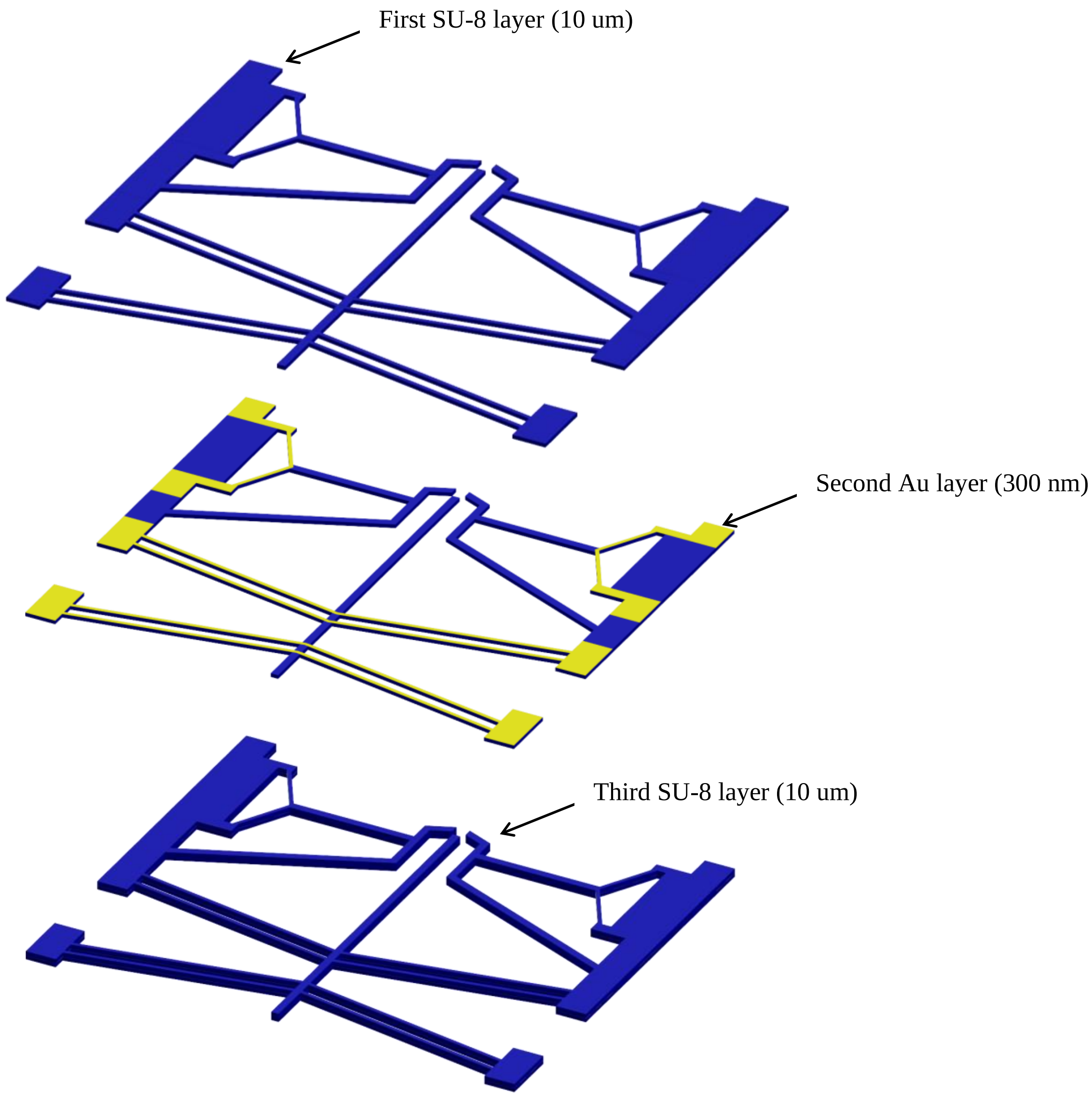


Figure 6-1 Layers in the order of fabrication

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To improve the adhesion of the gold layer to the SU-8 substrate, an O2 plasma treatment can be introduced [6]. This step ensures better cleaning and adhesion, leading to enhanced thermal and mechanical properties of the micro-grippers.

The fabrication process is designed with symmetry in mind, resulting in several advantages. Firstly, out-of-plane deflections were significantly reduced, improving the overall stability of the structure. Secondly, the symmetrical design ensures electrical isolation, making the micro-grippers suitable for handling biological micro-probes. Overall, the optimization of the fabrication process, including the removal of chromium layers and the introduction of O2 plasma treatment, not only simplifies the fabrication but also enhances the performance and versatility of the micro-grippers.

The fabrication process of the micro-grippers is to be done utilizing only a gold thin layer instead of the previously used Cr/Au/Cr layers [7]. This elimination of the chromium layers not only streamlines the fabrication process but also enhances the performance of the micro-grippers.

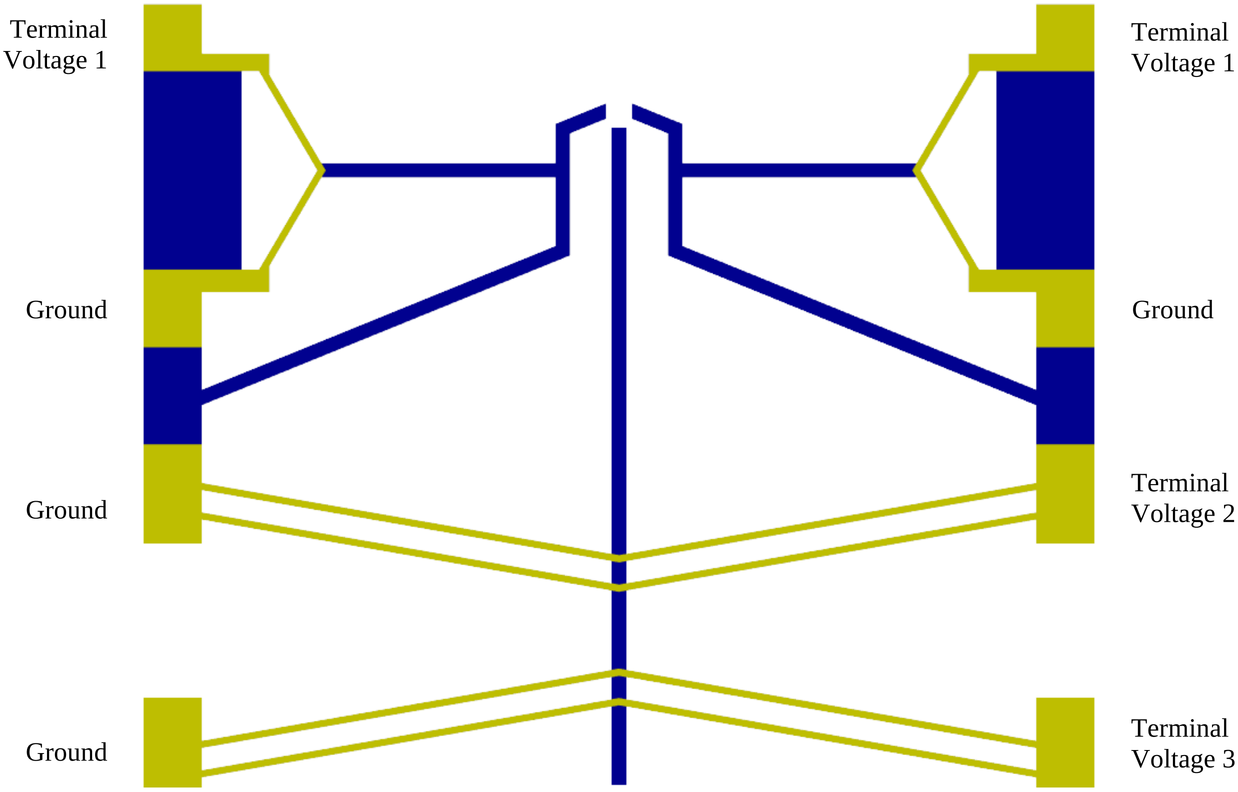


Figure 6-2 Electrical connection terminal arrangement

The main steps of the fabrication process can be detailed as follows,

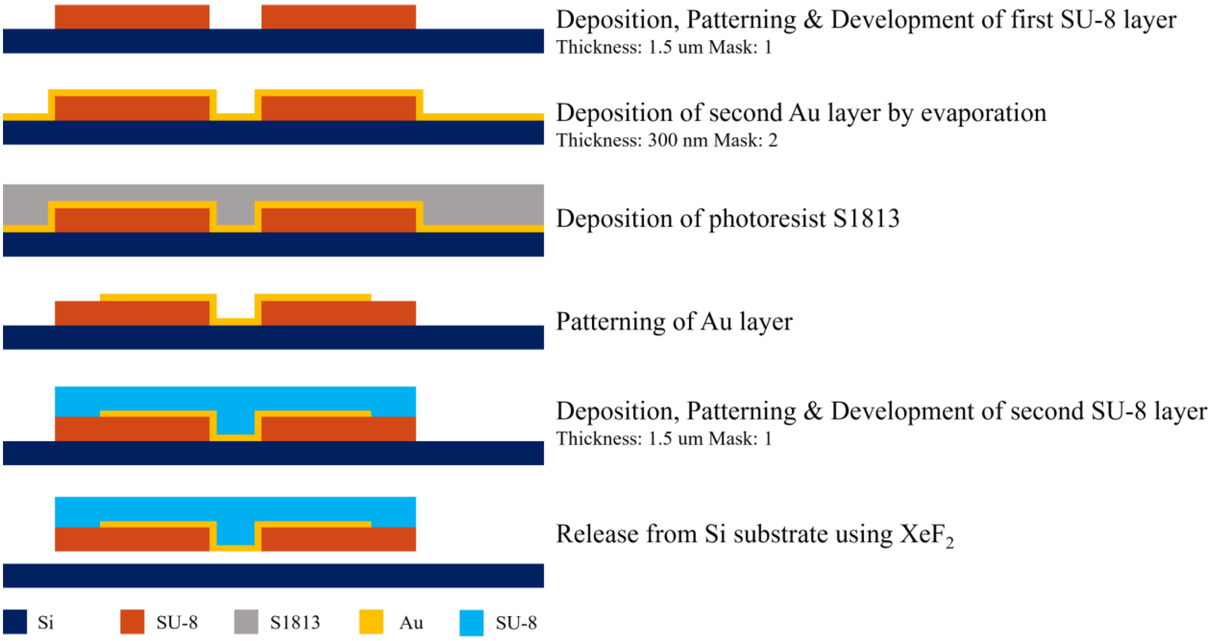


Figure 6-2 Main steps of fabrication

The SU-8 fabrication process involves five key steps,

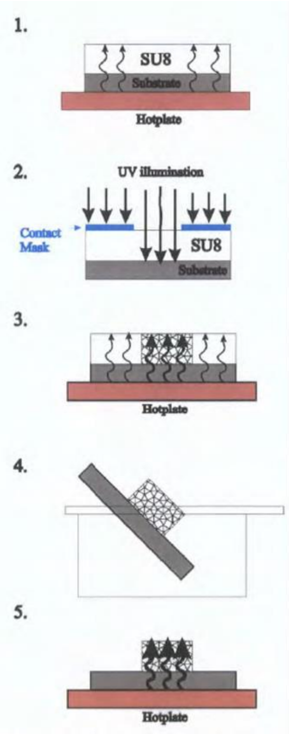
Deposition: Spin coating is the most common method for depositing SU-8 onto a substrate. The spin curves, which determine the final layer thickness, depend on the specific SU-8 formulation and its viscosity.

Soft Baking: This step removes the solvent from the SU-8 layer. The baking time depends on the desired layer thickness.

Exposure: The SU-8 layer is exposed to UV light through a mask containing transparent and opaque regions. This exposure initiates the crosslinking process in the SU-8.

Post Exposure Baking (PEB): This step further enhances the crosslinking of the exposed SU-8, ensuring proper pattern formation.

Development: The unexposed SU-8 is dissolved using a developer (GBL or PGMEA), while the exposed and crosslinked SU-8 remains intact, forming the desired pattern.



Deposition and soft baking
Standard spin-coater
Vacuum hotplate
Baking times depending on layer

UV exposure
Contact mask
Exposure dose depending on layer thickness and substrate material

Post exposure baking (PEB)
Vacuum hot plate
Baking times depending on layer thickness
Exposed/crosslinked SU8

Development
Immersion development
Times depending on layer thickness
Ultrasonic bath is sometimes recommended
Rinse with clean PGMEA

Hard Bake
Not always required but can help to relax the stress in the structures

Figure 6-3 Process steps of SU-8 Deposition to Development [4]

7 Mask Design

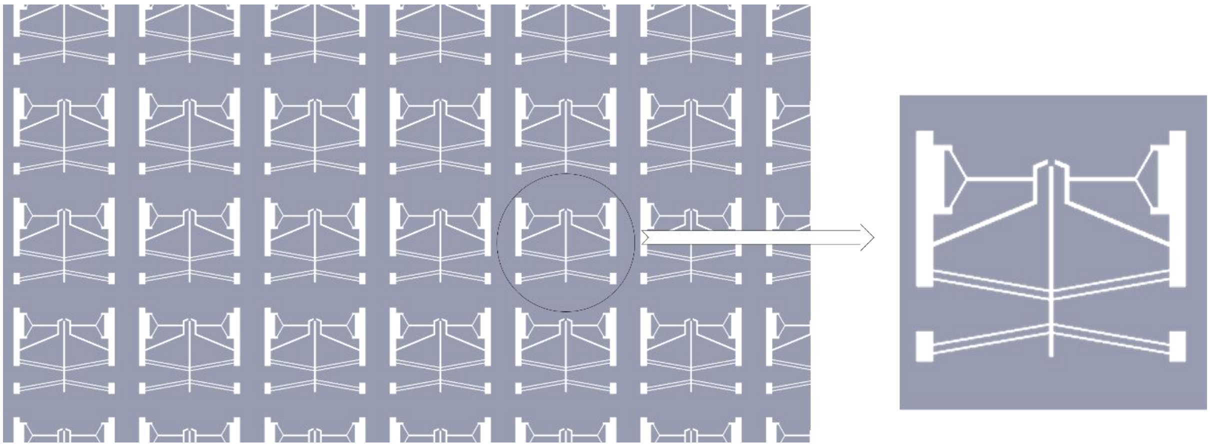


Figure 7-2 Mask for first and third layers of SU-8

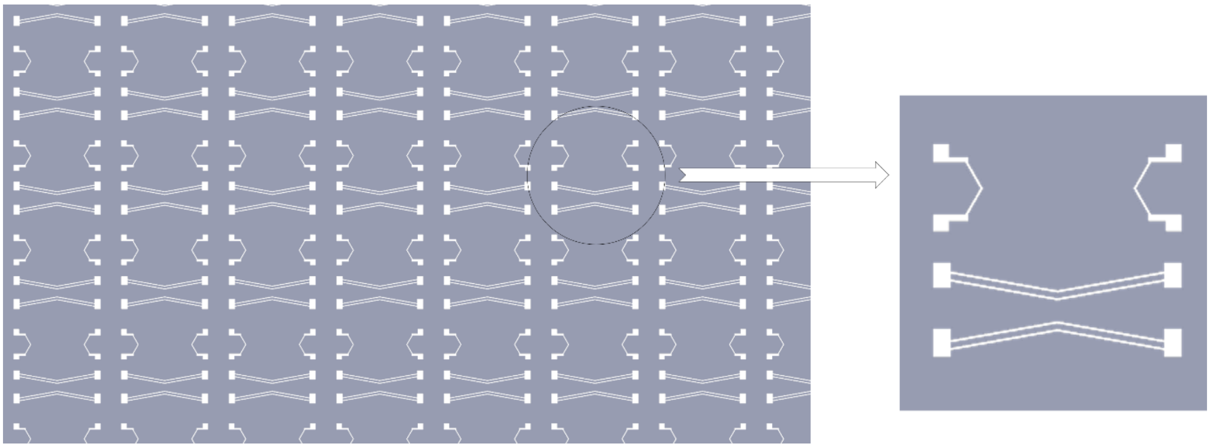


Figure 7-1 Mask for second (encapsulated) layer of Au

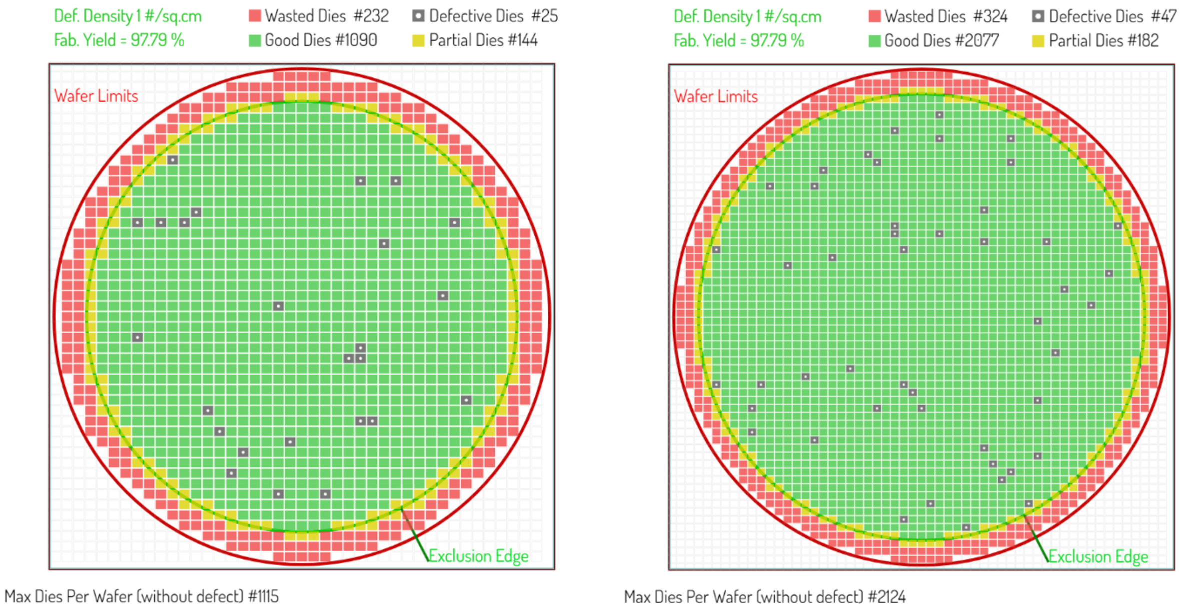


Figure 7-3 Dies per wafer for 3-inch (left) and 4-inch (right) wafers

Alignment marks are typically put on silicon wafers at two different stages of the semiconductor fabrication process. They are placed on the wafer before the deposition of any of the subsequent layers. This ensures that the patterns from subsequent layers will be properly aligned with each other. Alignment marks are also placed on the wafer after each lithography step. This ensures that the patterns from different lithography steps will be properly aligned with each other.

For placing alignment marks on a silicon wafer, photoresist can be used to create patterns on a wafer. The photoresist is exposed to light through a mask, and the areas that are exposed to light are selectively removed. The remaining photoresist can then be used as an etch mask to transfer the pattern onto the underlying silicon layer. Direct-write lithography is a process that uses a laser or other type of beam to directly write patterns onto a wafer which can also be used which is more precise than photoresist lithography, but it is also more expensive.

8 Circuit Design

For the microgripper device a simple Printed Circuit Board (PCB) was designed considering the Ground and Voltage terminals of the designed device configuration. Figure 8-1 indicates the circuit diagrams for the schematic and PCB layout. Figure 8-2 provides a 3D rendition of the same PCB.

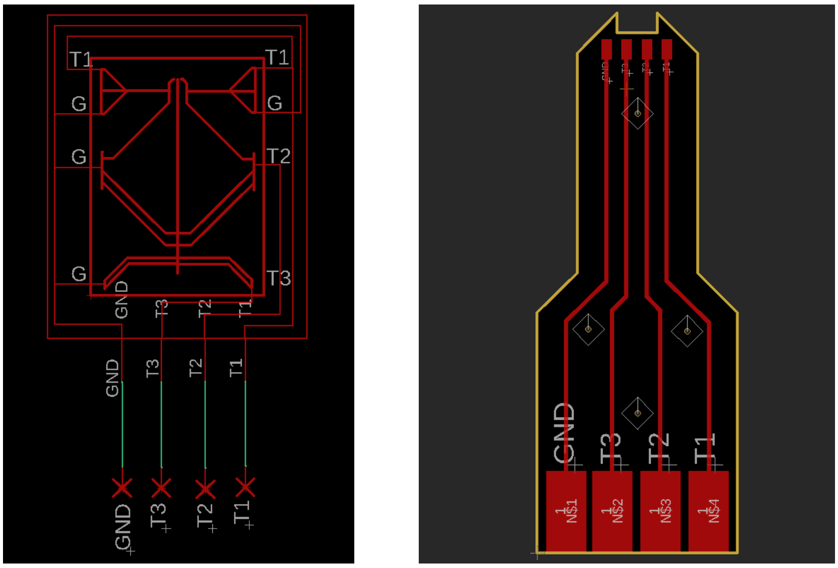


Figure 8-1 Schematic and layout of PCB design

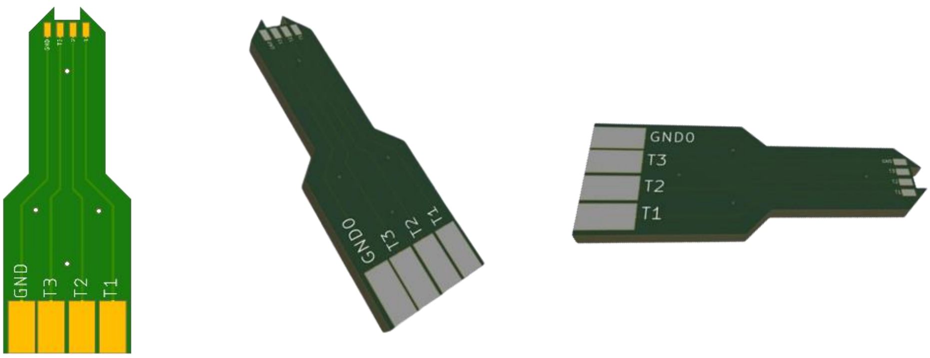


Figure 8-2 2D and 3D design of PCB component

9 Results and Discussion

To evaluate the performance of micro-grippers, electrical and displacement measurements can be conducted in an air environment. The gripper structure can be manually secured onto a silicon substrate. Subsequently, the in-plane displacements can be assessed using an optical microscope and a video camera [8]. Additionally, the deflections of the tips can be determined from optical images. The voltage and current at each displacement of one arm/tip can be measured and values corresponding to the maximum displacement can be obtained.

Similarly, to quantitatively analyze the performance of the active release mechanism, an experiment can be designed where glass microspheres are repeatedly picked and released and it is evaluated whether the release is successful or not while the projected distance is also measured.

9.1 Out of plane Displacement

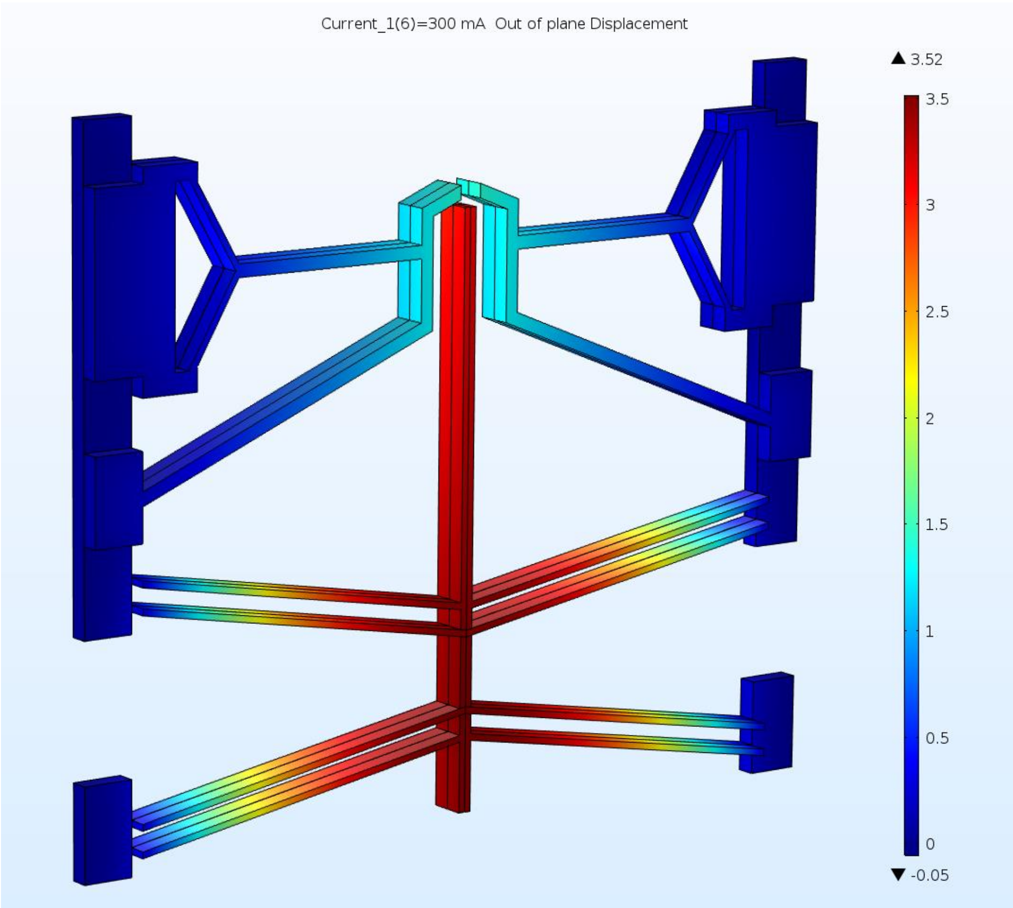


Figure 9-1 Out of displacement (µm) at maximum current

9.2 Behavior of the Jaw tip

9.2.1 Displacement

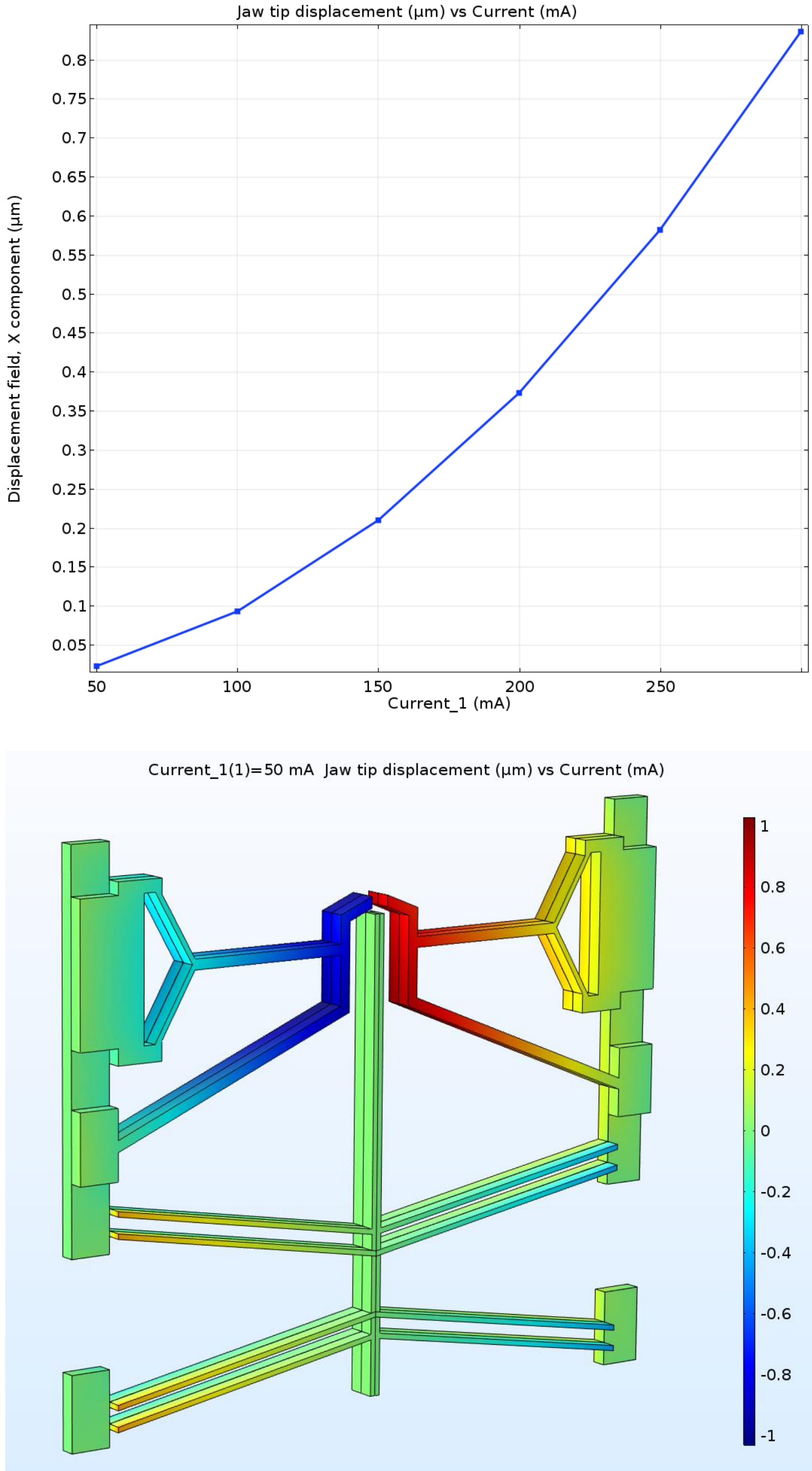
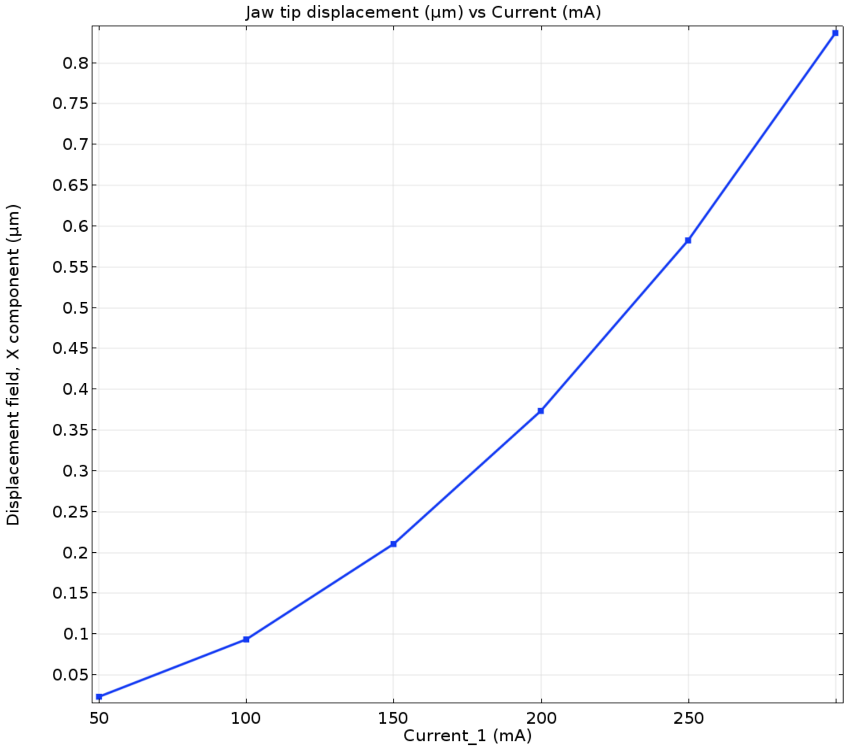


Figure 9-2 Jaw tip displacement (µm) vs Current (mA)

9.2.2 Temperature



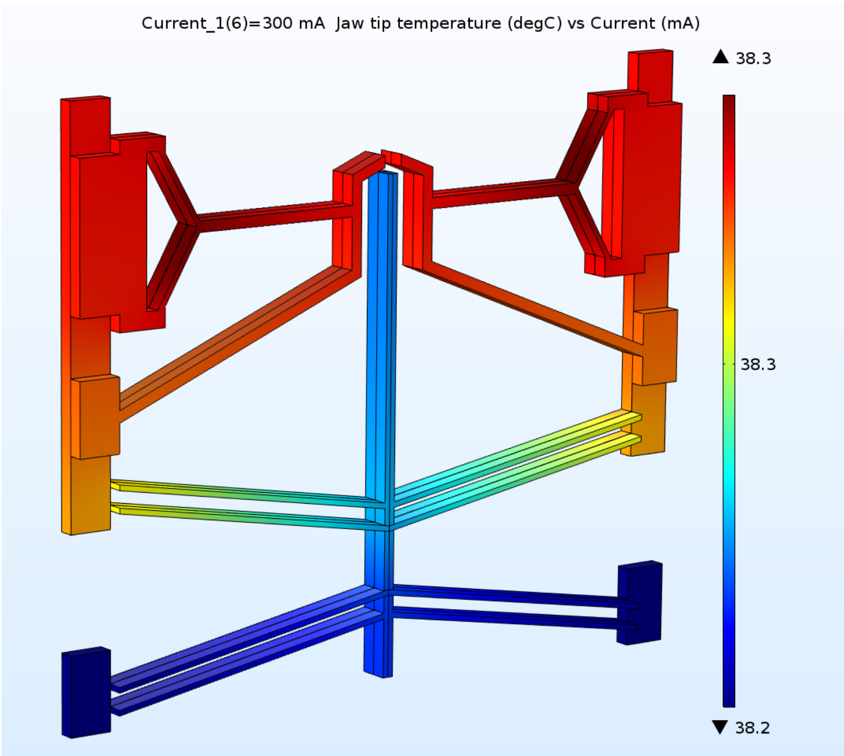
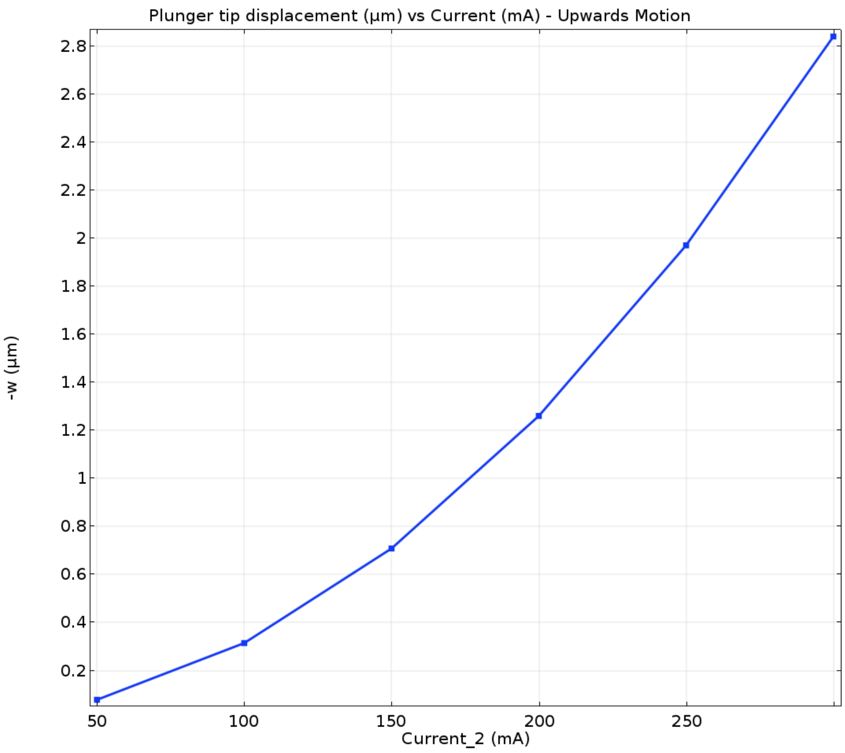
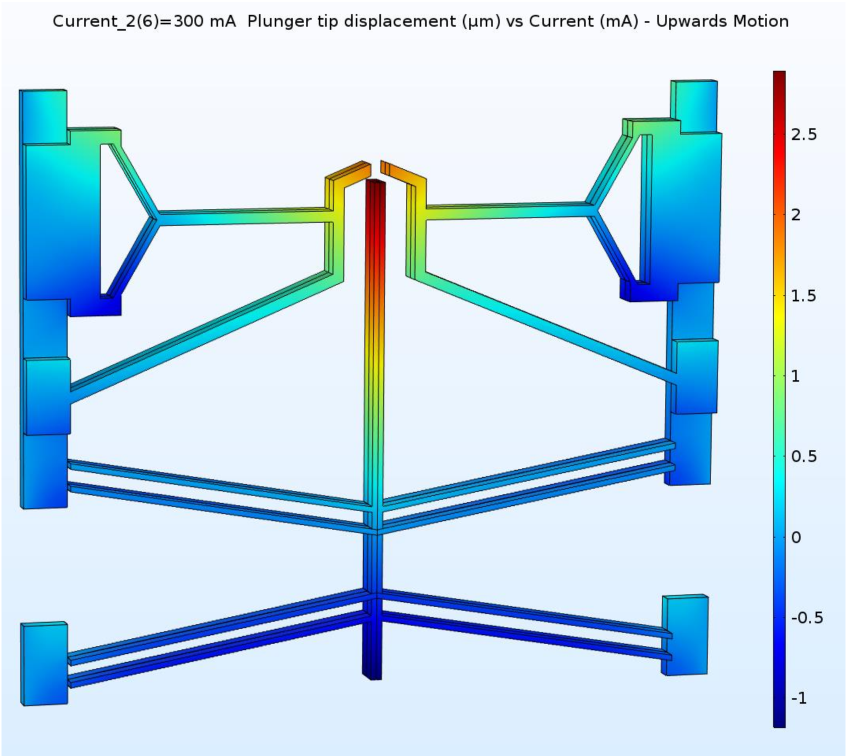


Figure 9-3 Jaw tip temperature (°C) vs Current (mA)

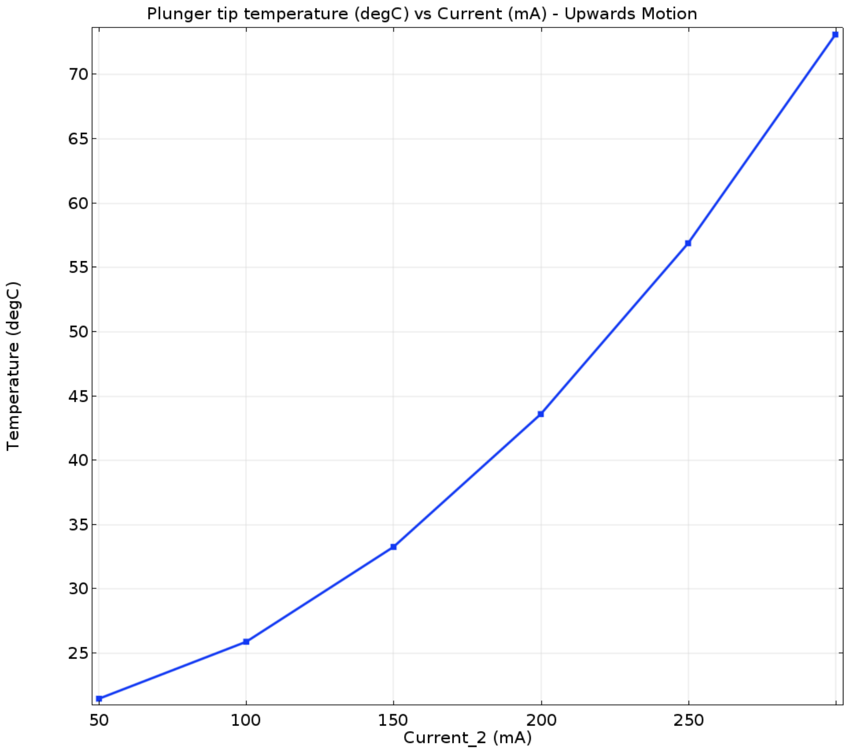
9.3 Behavior of the Plunger tip

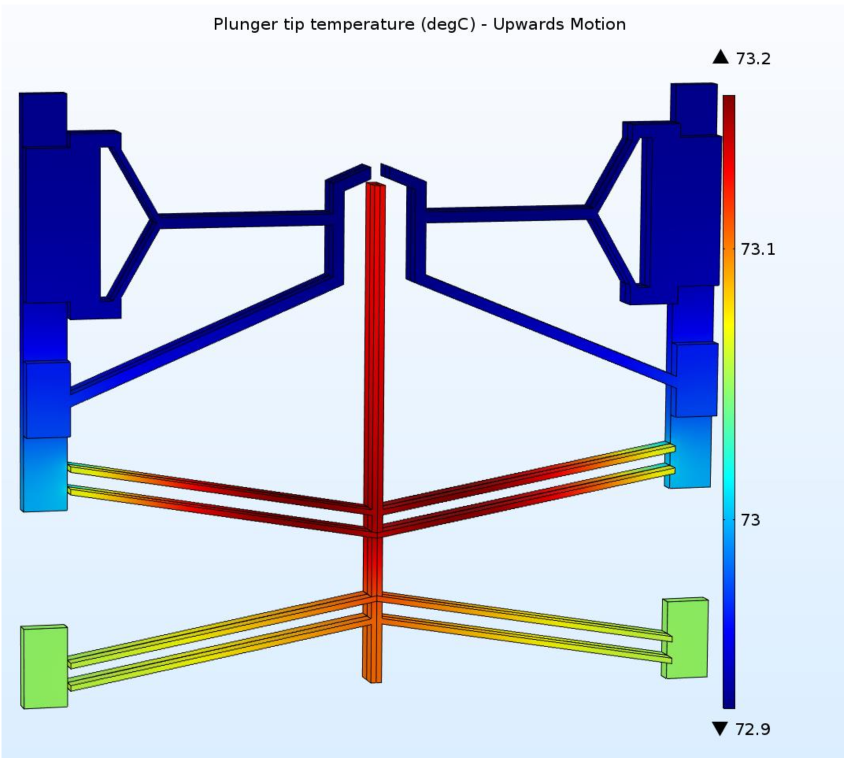
9.3.1 Displacement





9.3.2 Temperature





10 Conclusion

In this project two types of electro-thermally actuated microgrippers were designed and simulated: U-shaped and V-shaped. To simplify the fabrication process, a gold thin layer is employed as the heater, eliminating the need for an adhesion metal layer like chromium. The optimized design comprises three material layers with an encapsulated heater embedded in the polymer SU-8. This fabrication process can be employed to create a variety of polymeric-based MEMS devices that utilize electrothermal actuation to achieve in-plane deflection.

Numerical simulations revealed that the out-of-plane displacement of the gripper tips remained below 100 nm throughout the actuation process.

The temperature of the SU-8 microgripper tips remains near 30°C which is preferable for the biological micromanipulation applications.

The microgripper was fabricated using a three-mask photolithography process, ensuring high resolution and precise control over the final structure. The chosen structural material was SU-8, a biocompatible polymer known for its excellent mechanical properties and ease of processing.

To achieve efficient heating and minimize unwanted thermal effects, a metallic layer was embedded between two SU-8 layers of equal thickness. This configuration provides several key advantages:

Isolation: The metallic layer is completely encased within the SU-8, preventing electrical contact with external components and ensuring safe operation.

Improved Thermal Efficiency: By sandwiching the heater between SU-8 layers, heat generated during operation is effectively confined within the microgripper, leading to improved energy efficiency and faster response times.

Reduced Out-of-Plane Displacement: The SU-8 layers provide structural support and constrain the expansion of the metallic layer during heating, minimizing unwanted out-of-plane displacement and ensuring consistent gripper movement.

11 References

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