Design and Simulation of a Thermally Actuated Microgripper with a Compliant Bistable Release Mechanism for Biomanipulation

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***Abstract*—Microgrippers, devices based on MEMS (Micro-electro-mechanical systems) technology, are widely used to manipulate biological samples. When used for biomanipulation, they often confront the problem of stiction of samples to gripping jaws due to the behavior of materials at the microscale. The proposed design integrates a gripper with an active release mechanism that involves a compliant bistable mechanism enabling a quicker release that is conventionally difficult for electrothermal microgrippers. The proposed design features cascaded and double V-shaped thermoelectric actuators for effective micromanipulation. Along with selecting a suitable material for the microgrippers, a fabrication process has also been proposed. Simulation and analysis conducted using the COMSOL Multiphysics software have demonstrated operating temperatures and displacements in the preferable range for biomanipulation.**

***Index Terms*—electrothermal microgripper, active release, compliant bistable mechanism, biomanipulation**

I. Introduction

Microelectromechanical (MEMS) Microgrippers have been around for some time, and they operate on many different principles [1] such as piezoelectric, electrostatic, electromagnetic, shape-memory-alloy, etc. Electrothermal actuation is the preferred mechanism for biological manipulation due to its low voltage requirement, compatibility with conducting ionic fluids, and applicability in both air and liquid environments [2].

One of the persistent challenges in biological micromanipulation is the release of biosamples from the end effector due to the prevalence of strong adhesion forces at the microscale [3]. 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. This can be attributed to the inverse relationship between force and the characteristic length scale.

Release mechanisms can widely be categorized under active and passive release [3]. Passive release techniques attempt to detach micro-objects by natural adhesion forces. This can be done by rolling objects [4], or using special adhesives [5], but these methods can be slow, unreliable, and heavily dependent on specific materials. On the contrary, Active release techniques commonly involve using electric fields [6], mechanical vibration [7], or vacuum-based tools [8].

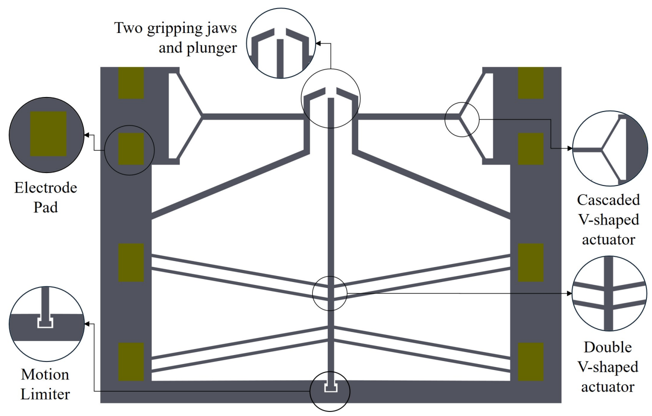


Fig. 1. Proposed Design of the Microgripper with its salient features

An innovative active release strategy for handling micro-objects is presented in [3] which incorporates a plunging structure situated between two gripping arms. The design keeps the benefits of double-ended tools for picking and placing micro-objects while the integrated plunger actively propels a micro-object, which is adhered to a gripping arm, to a specified location on a substrate. A dynamic release method involving inertial forces is incorporated with the microgripper introduced in [9].

Compliant bistable mechanisms have been incorporated into various MEMS devices. A V-beam combo structure has been incorporated to design a bistable switch in [10] while a curved beam specifically designed to be buckled is utilized in [11]. A working prototype of a compliant gripper powered by a bistable Shape Memory Alloy (SMA) actuation unit is presented in [12]. The fabrication of a bistable mechanism for a pneumatically actuated Microgripper has been explored in [13] proving its applicability across different devices.

Improving on existing designs for active release in microgrippers, the incorporation of a compliant bistable mechanism in our approach provides an effective active release method with high repeatability and minimal power consumption. A plunger located between two gripping arms enables the release of micro bio-objects while allowing the system to maintain its operational parameters within the appropriate range for biomanipulation.

The subsequent chapters offer an in-depth exploration of the proposed solution. Chapter II, 'Design and Simulation' examines the design methodology of the microgripper and the simulations that validate its performance. Chapter III, 'Results and Discussion' analyzes the simulation results. Chapter IV, 'Proposed Fabrication' outlines a potential fabrication process for the microgripper. Chapter V, 'Future Work' discusses possible improvements while Chapter VI, 'Conclusion' encapsulates the study's key findings and concluding observations.

II. Design and Simulation

A. Working Principle

Two types of actuators are widely incorporated in electrothermal microgrippers, specifically, U-shaped and V-shaped actuators. U-shaped actuators in electrothermal microgrippers work on the principle of uneven heating and expansion of a uniform material. They consist of beams of different lengths or cross-sections arranged in a U-shape. When an electric current is applied, it causes resistive heating, creating a temperature difference between parts with different geometries. The thinner, hotter arm expands more than the colder, flexure arms, causing a net in-plane deflection. On the other hand, V-shaped actuators function on the principle of asymmetrical heating and expansion of a materially homogeneous structure. Here, the beams are anchored by two supports at an angle, forming a V-shaped structure. When a current flows from one support to the other, Joule heating causes the beams to expand, resulting in an in-plane linear motion.

Since V-shaped actuators do not depend on an internal temperature gradient for their operation, it is more robust compared to U-shaped actuators. Consequently, the design proposed in Fig. 1 employs two forms of V-shaped actuators. Cascaded V-shaped actuators facilitate the opening and closing of the gripping jaws while the double V-shaped actuators facilitate the excitation of the plunger. The structural dimensions of the proposed design are presented in the Table I.

TABLE I
STRUCTURAL DIMENSIONS OF THE PROPOSED DESIGN

Structural Dimension	Value
Total length	1050 µm
Total width	1450 µm
Total thickness	3.3 µm
Jaw beam width	20 µm
Plunger beam width	15 µm
Cascaded V-beam length	75 µm
Cascaded V-beam width	10 µm
Cascaded V-beam angle	5°
Double V-beam length	550 µm
Double V-beam width	10 µm
Double V-beam angle	5°
Gap between V-beams	30 µm
Motion limiter width	20 µm
Motion limiter gap	30 µm

Fig. 2. Movement of jaws for picking and releasing (Motion amplified for more clarity) (a) Non-excited position (Normally open) (b) Excited position

For Modeling Electrothermal actuation, heat conduction was the only type of heat transfer considered [14], [15] which was further simplified by considering one-dimensional heat conduction given by equations 1, 2, and 3.

$$k\frac{d^2T}{dx^2} + \dot{q}_b + \dot{q}_s = 0 \quad (1)$$

$$\dot{q}_b = \frac{A^2{}_{s\_A_u}}{\rho(2A_{s\_A_u}L_b + nL_sA_{b\_A_u})^2}V^2 \quad (2)$$

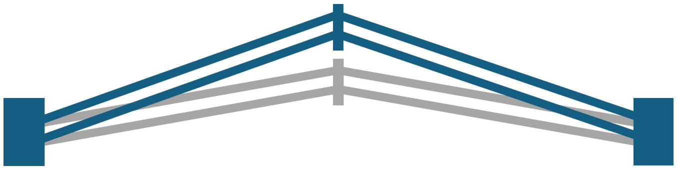
$$\dot{q}_s = \frac{(nA_{b\_A_u})^2}{\rho(2A_{s\_A_u}L_b + nL_sA_{b\_A_u})^2}V^2 \quad (3)$$

$$\Delta L = \alpha \Delta T_{\text{avg}} L_b, \quad (4)$$

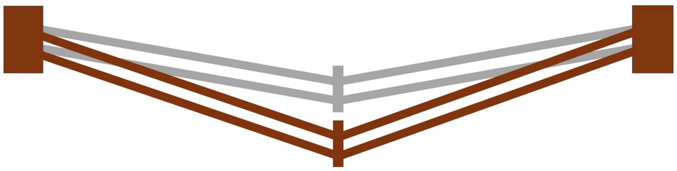
k represents the thermal conductivity of the gold heater. $\dot{q}_b$ and $\dot{q}_s$ represent the joule heat source in the microbeam and shuttle, respectively. The electric resistivity of gold is denoted by ρ. The number of pairs of V-shaped microbeams is represented by n. The cross-sectional area of the gold layer in the shuttle and beam are represented by $A_{s\_A_u}$ and $A_{b\_A_u}$, respectively. At the steady state, The average temperature increase in SU-8 causes the microbeams to elongate, as given by equation 4, where α is SU-8's thermal expansion coefficient.

B. Gripper Actuation

As depicted in Fig. 2, the operation of the jaws is enabled by the cascaded V-shaped actuators. The design is based on a normally open configuration, which means that when the actuators are excited, the jaws close, enabling them to grasp an object. The jaws remain in the closed position as long as the respective nodes are powered. Once the excitation is removed, the jaws revert to their original open position, allowing the release of the grasped object. This mechanism ensures intuitive control over the gripping and releasing actions of the micropgripper.



(a) Ejecting Actuator



(b) Restoring Actuator

Fig. 3. (a) Ejecting Actuator of the Plunger which upon activation travels upward to release the grabbed object (b) Restoring Actuator of the Plunger which upon activation travels downward to restore the plunger; Light & Dark colors show the non-excited and excited positions, respectively (Motion amplified for more clarity)

C. Plunger Actuation

The design's novelty lies [] in the plunger that utilizes a Compliant Bistable Mechanism to release micro-objects from its jaws. Compliant Bistable mechanisms have the unique characteristic of possessing two stable states that are intrinsically linked to the mechanism's function and, despite relatively simple design and configuration, are beneficial in numerous applications. These mechanisms can maintain [r2] two positions in stable equilibrium without the need for a constant force to hold them in place. A temporary input force is only required to allow a transition from one state to the other.

The 'ejecting actuator' which forms its V-shape pointing in the direction of the jaws, depicted in Fig. 3a, enables the upward motion of the plunger to eject the micro-object out of the jaws. Conversely, the 'restoring actuator' which forms its V-shape pointing in the direction opposite to the jaws, depicted in Fig. 3b, provides the restoring force to reinstate the plunger to its original position.

At any given time, only one of the two actuators, either the ejecting or restoring actuator, is powered to function as a straightforward, and intuitive (bistable) switch. The activation of the V-beams in the ejecting actuator induces a buckling effect in the V-beams of the restoring actuator, and vice versa. This buckling action is what establishes the stable states of the plunger mechanism. A temporary activation is only required to transition from one state to another. Once a state is reached, it remains in that state until an opposing activation is applied.

Another unique addition to complement the plunger's function is the Motion Limiter, shown in Fig. 1, which limits excessive expansion and assists in switching the states between excited and non-excited positions. By the limitation of the range of motion, the operation of the plunger mechanism within its optimal parameters is ensured, thereby preventing any undue strain or damage acting as a safeguard in essence.

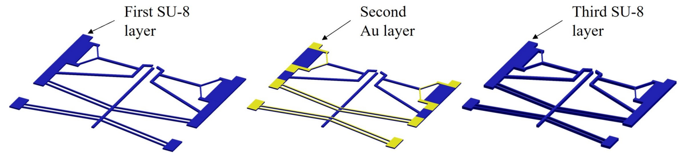


Fig. 4. Encapsulation of a gold layer between layers of SU-8

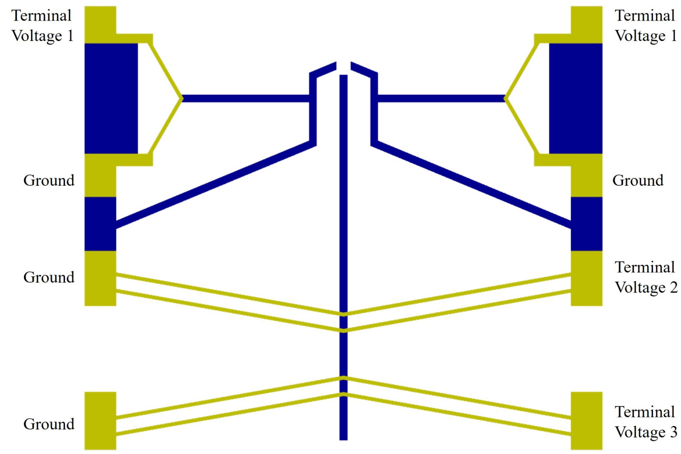


Fig. 5. Electrical terminal arrangement

D. Material Selection

Material selection is a critical design decision that influences the optimal operating conditions of the microgripper and is fundamental to the simulation process.

Silicon-based microgrippers, while useful, can pose challenges in biological applications due to high operating temperatures, electrical conductivity, and excessive gripping forces. Although Si-polymer composites could mitigate these issues, their complex fabrication processes may offset the benefits. On the other hand, polymer fabrication offers advantages such as cost-effectiveness and ease of processing, making it a suitable choice for disposable devices in biological and medical applications.

SU-8 is an ideal material for fabricating microgrippers used in biological tissue and cell operations. Its ability to form high aspect ratio structures and its excellent biocompatibility have led to the successful development of several SU-8 microgrippers with different driving mechanisms [3]. Its highly crosslinked nature provides robust mechanical properties, essential for the delicate task of handling biological materials.

SU-8 is biocompatible, ensuring safe interaction with living tissues. Its thermal properties, including a high glass transition temperature for stability and a significant coefficient of thermal expansion, make it well-suited for electrothermal actuation mechanisms often used in microgrippers [16]. Resistance to most organic solvents and acids, and compatibility with standard silicon processing and most analytical chemicals are also added benefits. Furthermore, its unreacted epoxy groups allow it to be functionalized for biological applications, making SU-8 an optimal choice.

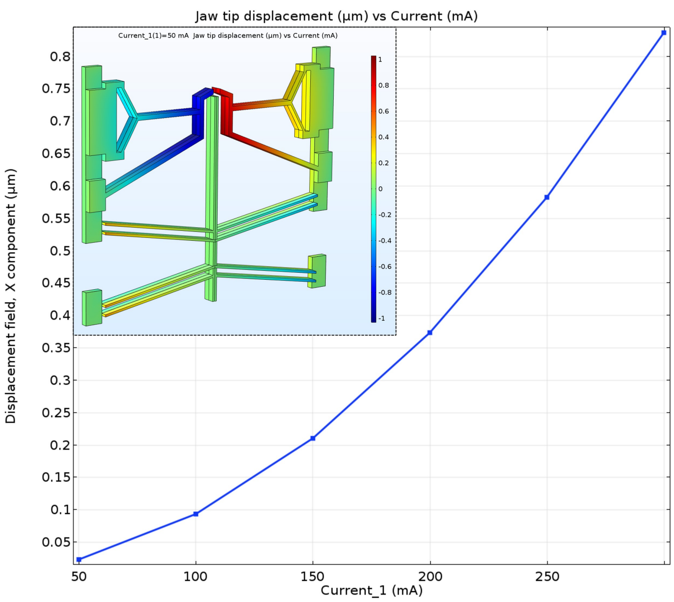


Fig. 6. Jaw tip displacement (µm) vs Current (mA)

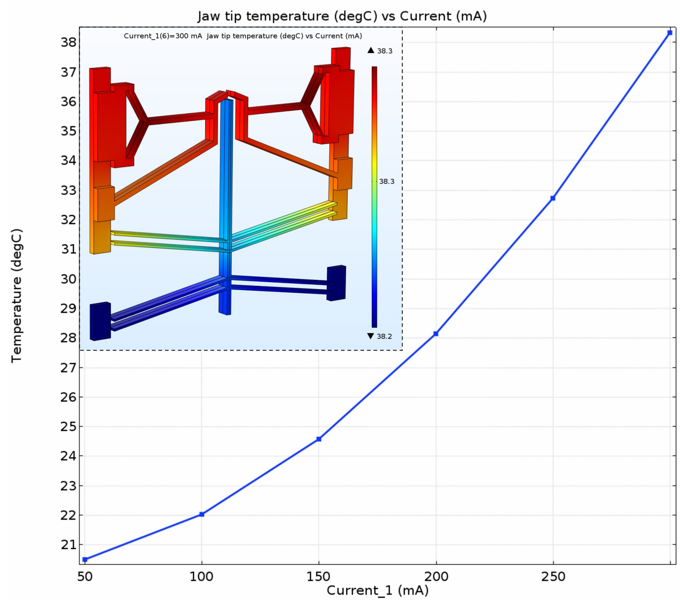


Fig. 7. Jaw tip temperature (°C) vs Current (mA)

In addition, since SU-8 can act as an adhesion layer for the gold metallization and encapsulate the microgripper's resistors it further suits the requirements. Metallic microheaters can be 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 (Fig. 4) 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.

E. Electrical Connections

The configuration of voltage nodes and ground nodes is linked to the actuation types employed by the microgripper. Each actuator - the jaw actuator, the ejector actuator, and the restoring actuator - operates independently. This independent operation necessitates the allocation of separate voltage nodes for each actuator as illustrated in Fig. 5.

F. Simulation

The proposed design operates on the principles of Joule heating and thermal expansion. Electric current flowing through the beam generates heat, causing its resistance to vary and the beam to expand. This expansion creates mechanical displacement, providing the actuation force. COMSOL Multiphysics software is used to analyze actuation potential, temperature, displacement, and stress within the mechanism.

III. Results and Discussion

A. Analysis

The variation of the displacement and the temperature of the tip of the jaws and the plunger are examined as key indicators of the overall behavior of the jaws and the plunger. The line plots and the 3D representations of the variations are given in Fig. 6 & Fig. 7 for the jaws and Fig. 8 & Fig. 9 for the plunger. Additionally, the out-of-plane displacement of the microgripper under simulation is visualized in Fig. 10.

For effective biomanipulation, an operating temperature below 100 °C and a jaw displacement within the range of $2\,\mu m$ to $150\,\mu m$ are considered optimal [2]. The observed temperatures at the tips of the gripping jaws and plunger remained within this preferred range, and the jaw displacement was also within the specified limits. Structural simulations confirmed that the out-of-plane displacement of the gripper tips stayed below 100 nm throughout the actuation process, further validating the effectiveness of the proposed design.

IV. Proposed Fabrication

The fabrication process of the microgripper involves a three-mask surface micromachining process given by Fig. 11. Initially, an SU-8 layer of $1.5\,\mu m$ thickness is deposited, followed by a comparatively thinner layer of gold of $300\,nm$ thickness, and then another layer of SU-8 of $1.5\,\mu m$ thickness. To enhance the adhesion of the gold layer to the SU-8 substrate, an O_2 plasma treatment is introduced. This step not only ensures better cleaning and adhesion but also leads to improved thermal and mechanical properties of the microgrippers.

The fabrication of a single SU-8 layer for MEMS microgrippers involves a five-step process. Initially, the SU-8 is deposited onto a substrate using spin coating, with the final layer thickness determined by the specific SU-8 formulation and its viscosity. This is followed by soft baking to remove the solvent from the SU-8 layer, with the baking time adjusted based on the desired layer thickness. The SU-8 layer is then exposed to UV light through a mask, initiating the crosslinking process. Post-exposure baking enhances the crosslinking of

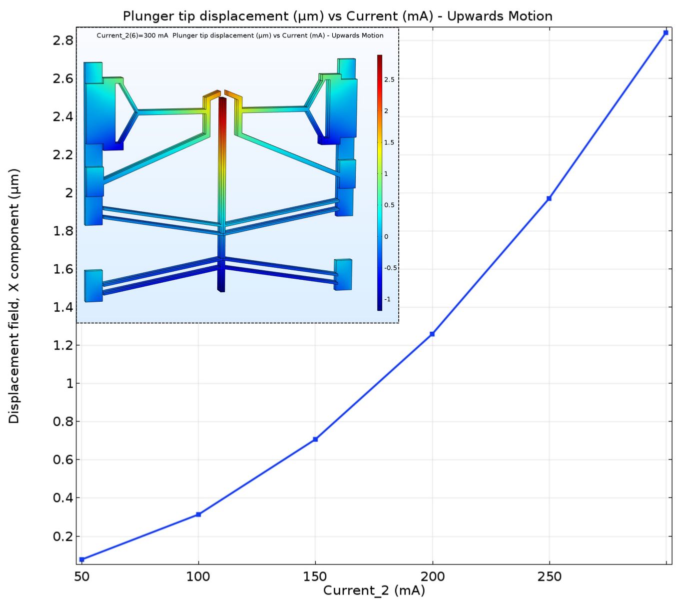


Fig. 8. Plunger tip displacement (µm) vs Current (mA)

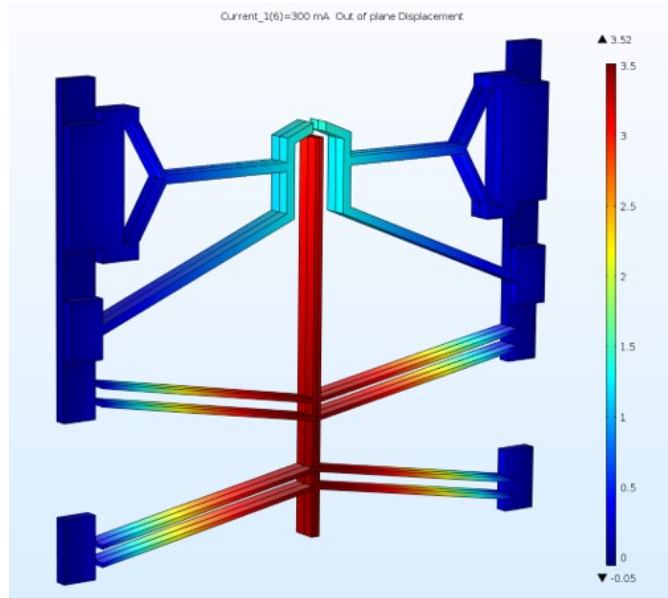


Fig. 10. Out of plane displacement

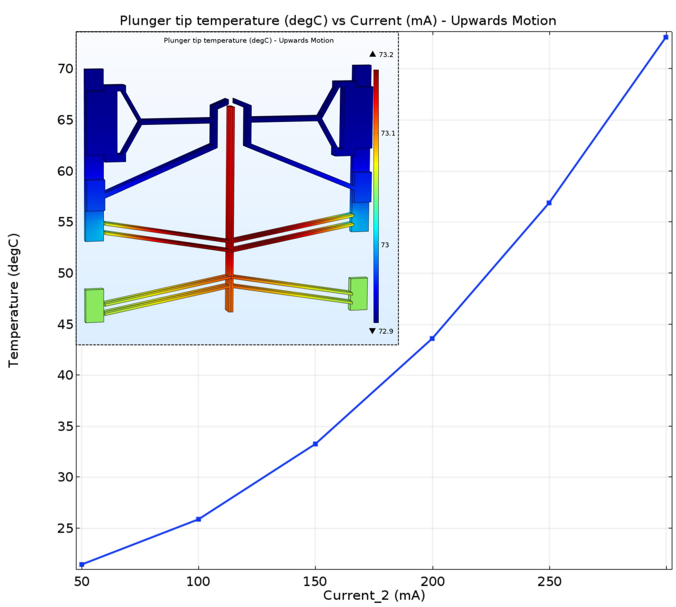


Fig. 9. Plunger tip temperature (°C) vs Current (mA)

the exposed SU-8, ensuring proper pattern formation. Finally, the unexposed SU-8 is dissolved using a developer, leaving the exposed and crosslinked SU-8 intact, forming the desired pattern.

The encapsulation is done with symmetry in mind, offering several advantages. Out-of-plane deflections are significantly reduced, thereby improving the overall stability of the structure. Furthermore, the symmetrical design ensures electrical isolation, making the microgripper suitable for handling biological microprobes. Contrary to the majority of previous methods, the fabrication process of the microgripper utilizes only a thin gold layer, eliminating the previously used Cr/Au/Cr layers [16]. This streamlining of the fabrication process enhances the performance of the microgripper.

The proposed configuration provides several key advantages such as isolation. The metallic layer is completely encased within the SU-8, preventing electrical contact with external components and ensuring safe operation. Furthermore, 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.

V. Future Work

For evaluating the performance of microgrippers, 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 [17]. 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 biological specimens are repeatedly picked and released and it is evaluated whether the release is successful or not while the projected distance is measured. Integrating a force sensor with the jaws to quantitively measure the force applied, as in [18], would further enhance its capabilities.

Factors including compatibility in air and liquid mediums, low-temperature and low-voltage functionality, appropriate displacement range, gentle handling, insulation, disposability, and the ability to undergo sterilization [2] must also be considered for a comprehensive design that operates safely and effectively within biological environments.

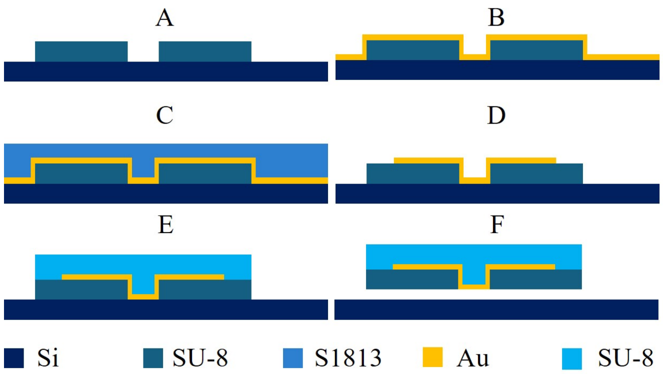


Fig. 11. Steps of proposed fabrication process

As design improvements, it is suggested to investigate the behavior of curved beams as a replacement for straight beams [11], [13] which could determine if such a design modification could enhance the performance of the system.

VI. Conclusion

In this study, an electrothermally actuated microgripper featuring a novel Compliant Bistable Release Mechanism was designed and simulated. The simulation results were promising, demonstrating satisfactory performance for biomanipulation in terms of the temperature and displacement of the tips of the jaws and the plunger. Moreover, minimal out-of-plane displacement indicated effective control in practical applications.

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

Future work should investigate the use of curved beams as a replacement for straight beams which could potentially enhance system performance. Additionally, factors such as compatibility in various mediums, low-temperature and low-voltage functionality, displacement range, handling, insulation, disposability, and sterilization are to be considered for a comprehensive design.

TABLE II
Detailed Steps of Fabrication Process

Step	Explanation	Criteria
A	Deposition, Patterning, and Development of the first SU-8 layer	Thickness: 1.5 µm Mask: 1
B	Deposition of gold layer by evaporation	Thickness: 300 nm
C	Deposition of photoresist S1813	-
D	Patterning of gold layer	Mask: 2
E	Deposition, Patterning and Development of the second SU-8 layer	Thickness: 1.5 µm Mask: 3
F	Release from Si substrate using XeF2	-

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