MEMS Based Microgripper for Biological Cell Manipulation

1 INTRODUCTION

Micro-Electro-Mechanical Systems and Nano-Electro-Mechanical Systems are the advanced technologies combining electrical and mechanical parts in microscale and nanoscale levels, respectively. These systems have wide applications in sensing, actuation, biomedicine, and nanotechnology.

Precise and delicate manipulation of biological cells is essential in biomedical research, drug development, and tissue engineering. Most conventional methods cause cell damage or deformation; hence, the need for ingenuity. MEMS-based microgrippers have high precision and control, making them an ideal tool in handling cells at the microscale.

This project aims at the design and simulation of a MEMS-based microgripper for manipulating biological cells, with diameters ranging from 10 to 100 microns. The design provides an integrated force-sensing feedback system to avoid excess gripping forces, ensuring safety and efficiency in cell handling. It is expected that this will further the technologies of cell manipulation and improve experimental reliability in biomedical applications.

2 MOTIVATION

Manipulating biological cells is a critical yet challenging task in biomedical research due to their delicate nature. Excessive forces during handling can cause irreversible damage, deformation, or cell death, undermining experimental reliability. While MEMS-based microgrippers offer precision, they often lack the ability to measure and regulate applied forces in real time, leading to suboptimal handling, particularly for cells with sensitive membranes.

Also, most of the microgrippers developed so far are designed for specific cell sizes, which makes them limited in handling a range of dimensions. The lack of on-board force-sensing feedback systems further limits their functionality, since precise control and monitoring during manipulation are very important.

This project overcomes these limitations by designing and simulating a MEMS-based microgripper integrated with a force feedback system. The proposed design allows for precise force measurement and adaptability to cell sizes in the range of 10-100 microns, thus enhancing the reliability of cell handling and extending its applications to high-throughput biological assays for the advancement of cell manipulation technologies.

3 LITERATURE REVIEW

3.1 Subsection 1: Project environment

Biological Cells

Biologists regard a biological cell as the basic unit of life, although it varies in size, structure, and function among different organisms. The cell size ranges from 10 to 100 μm-a range within which microscale and nanoscale manipulations are quite feasible. The ability to manipulate these cells with precision has been of increasing importance in research, diagnostics, and therapeutics of biomedical interest. Manipulation of biological samples while preserving native structure and function is indeed challenging in dynamic or liquid environments.

Bio-cell manipulation allows progress in such fields as single-cell analysis, genetic engineering, and tissue engineering. For instance, knowledge of the mechanics of individual cells is useful for developing advanced disease models and therapeutic strategies. Precise handling of cells is indispensable in drug discovery processes and regenerative medicine, where cell placement and interaction are critical.

Challenges in Cell Manipulation

Handling biological cells is challenging due to their fragility and susceptibility to mechanical, thermal, and chemical damage. Precise control of forces applied during manipulation is critical to prevent cell deformation or rupture. Additionally, scaling effects exacerbate these challenges, as forces insignificant at the macroscale become dominant at the microscale [Manipulation of Living Biological Cells: Challenges in Automation]. For instance, cell stability is highly influenced by van der Waals forces and surface tension, which demand precise calibration of the handling tools.

Techniques for Cell Manipulation

<u>Mechanical Manipulation</u>

Direct contact is provided by the mechanical tools, which include the microgrippers and atomic force microscopes. The microgrippers can be employed for applications needing very well-controlled forces, and manipulations have often incorporated several feedback mechanisms like capacitive sensors to increase accuracy. In parallel with such mechanisms, AFM also evolved into a device for pushing, pulling, or indenting cells over properties understanding.

Optical Tweezers

Optical tweezers present a non-invasive means of cell manipulation by developing forces in the piconewton range using focused laser beams. This system is effective under liquid surroundings, hence an ideal mechanism for single-cell studies, excluding physical contact.

Di electrophoresis (DEP)

DEP utilizes non-uniform electric fields in translating or sorting cells based on their dielectric properties. The technique is hence widely used in microfluidic platforms to sort diseased cells from healthy ones and align cells for diagnostics.

Microfluidic Systems

Microfluidic systems are central in cell manipulation, which allows for the precise regulation of fluidic environments. Hydrodynamic forces, along with channel geometry manipulation, are some of the techniques used to achieve high-throughput cell handling in applications such as single-cell sequencing.

Applications of Bio-Cell Manipulation

Bio-cell manipulation is an essential tool within biomedical research that allows for detailed study into cellular behaviour and mechanics. Such provides invaluable insight into the structural and functional properties of cells, thus playing to the elucidation of basic biological processes. In diagnostics, manipulation techniques enable early disease detection through single-cell analysis that helps in identifying pathological changes at the cellular level with high precision.

In drug discovery, bio-cell manipulation is required for the study of real-time interactions between drugs and individual cells. This helps in assessing the efficacy and toxicity of drugs, which leads to developing safer and more effective therapeutics. In addition, in tissue engineering, manipulation of cells into complex 3D structures supports the creation of functional tissues and organs for regenerative medicine, addressing critical needs in transplantation and repair of damaged tissues.

3.2 Subsection 2: MEMS Based Actuation

Accurate actuation mechanisms are vital for the operation of microgrippers in manipulating biological cells. The major actuation techniques that have been developed include

piezoelectric, electrostatic, and thermal mechanisms. Each method provides advantages related to precision, force output, and MEMS fabrication integration.

Piezoelectric Actuation

Piezoelectric actuators rely on the inverse piezoelectric effect, which involves mechanical deformation proportional to an applied electric field. This actuation method is very suitable for microgrippers since it offers very fine control and fast response. Some of the piezoelectric materials, such as PZT, have high displacement efficiency and are thus suitable for applications involving small but accurate movements.

Electrostatic Actuation

Electrostatic actuation relies on the attraction between charged electrodes to provide force. It offers low power consumption and is compatible with MEMS processes. However, the force output is usually limited, which restricts its applications to low-load situations.

Thermal Actuation

Thermal actuators rely on material expansion generated through resistive heating. They have large force and displacement but are slower and inefficient in energy; thus, they find application in tasks where the need for speed is minimal.

Gripper designs have been tailored for a given actuation mechanism and manipulation task, with a special emphasis on precision, safety, and adaptability. They have rounded or tapered tips to prevent cell damage, as well as microstructured surfaces to reduce adhesion and deformation. Electrothermal grippers will also have V-beam designs for high displacement and force with heat sinks to reduce thermal impacts. Piezoelectric grippers contain multi-degree-of-freedom mechanisms for precise, soft-touch movements. Capacitive sensors near the tips provide real-time force adjustments to ensure uniform force distribution for safeguarding cell viability. Corrosion-resistant and anti-adhesive coatings enhance functionality in air and liquid environments, while polymers or damping materials reduce vibrations for stable operation in piezoelectric and electrothermal grippers.

The design of grippers should also consider the size range of biological cells, 10–100 μm, with a uniform application of force to avoid cell damage. In electrothermal actuators, thermal management is an important factor; hence, heat sinks or insulating materials reduce thermal

damage. Soft-touch mechanisms and dynamic tip retraction allow for minimal force application and smooth release of cells, enabling precise manipulation without damage.

3.3 Subsection 3: MEMS Based Sensing

The sense of forces is a very important element in MEMS microgrippers, mainly when manipulations of biological cells occur. The goal is the precise measurement of the acting forces during the gripping for the protection against cell damages. In MEMS systems, force sensing is attained by detecting deflections, strains, or physical properties variation due to applied forces. A few sensing technologies are employed for their application compatibility, sensitivity, and resolution.

Piezoresistive Force Sensing

This method is based on the piezoresistive effect, in which mechanical stress applied to a material induces changes in its electrical resistance. The main advantages of piezoresistive sensors are compactness and relatively easy integration into MEMS designs. However, they have lower sensitivity compared with capacitive sensors and are also susceptible to thermal noise, which will affect the measurement in fluctuating environments.

Capacitive Force Sensing

Capacitive sensors rely on the measurement of changes in capacitance due to the displacement of conductive plates under applied forces. This technique is very suitable for MEMS grippers, as it offers high sensitivity and nanoNewton-level force measurements. Capacitive sensors are among the most common sensors used in microgrippers for real-time feedback during biological cell manipulation. However, they require precise calibration and are prone to electrical noise, especially in liquid environments. Proper insulation and grounding techniques are crucial for ensuring accuracy.

Optical Force Sensing

The optical technique relies on changes in the light signal to measure the forces applied. The techniques have very high precision and resolution. However, they are rather bulky and expensive. Therefore, their application in MEMS is limited. They are more laboratory-oriented than integrated-systems-based.

Piezoelectric Force Sensing

Piezoelectric sensors convert mechanical stress into electrical signals. These sensors are suitable for dynamic force sensing and high-speed applications. However, they depend on high-quality piezoelectric materials and are sensitive to temperature variations, thus requiring careful material selection for MEMS applications.

Force Sensing Challenges in Manipulation of Biological Cells

- Sensors with nanoNewton sensitivity are needed for the precise handling of biological cells to keep the forces within the limit to avoid rupture or deformation.
- Electrical and thermal noise in aqueous environments can impede sensor performance, and therefore protective coatings and shielding are needed to ensure reliable operation.
- For making dynamic adjustments in forces during manipulation while maintaining control and cell integrity, fast response times will be necessary.
- Sensor designs will need to be compact to integrate effectively into MEMS grippers while preserving functionality within the small size constraint.

3.4 Subsection 4: MEMS Fabrication

Fabrication of MEMS microgrippers generally involves precision microfabrication techniques that ensure multiple components, such as actuation mechanisms, sensors, and gripping tips, are integrated.

Bulk Micromachining

This is a very common method for creating structural elements of the gripper, including jaws and amplifiers. It involves the use of etching techniques, such as deep reactive ion etching (DRIE), to define high-aspect-ratio features.

Surface Micromachining

Applied for thin-film components, like piezoelectric layers or capacitive sensors. The process allows the integration of a number of functional layers.

Lithography and Etching

Photolithography is used to define fine patterns; material is removed either by chemical or plasma etching to build up micro-structures.

Deposition Techniques

Silicon nitride or PZT may be deposited in thin film forms by CVD processes or sputtering. The thin film uniformity from such methods is highly necessary in terms of actuation and sensing.

Assembly and Packaging

Final assembly involves bonding and aligning components, ensuring the gripper's functionality in operational environments. Packaging has to consider biocompatibility and environmental protection, especially for applications in aqueous conditions.

Materials for MEMS Microgripper

MEMS microgrippers require materials that balance mechanical strength, biocompatibility, and manufacturability. Common choices include Si for its stiffness and compatibility with MEMS, while being brittle under high stresses; Si_3N_4 for its better strength and wear resistance, suited for the fabrication of strong parts such as jaw arms; polysilicon for its excellent mechanical properties but requiring surface coatings for being biocompatible; piezoelectric materials like PZT, useful for their high actuation efficiency despite their brittleness; and PDMS, normally used as a coating material to improve biocompatibility and reduce stress on biological cells.

4 PROPOSED DESIGN

4.1 Selecting the suitable methods

Actuation method

Criteria	Electrostatic	Electrothermal	Piezoelectric	Magnetic	SMA
Working Principle	Coulomb forces between charged plates.	Thermal expansion generates motion.	Voltage-induced deformation of piezoelectric material.	Lorentz forces generated by magnetic fields.	Phase transition in materials like Nitinol.

Actuation Range	Moderate.	High.	Low to moderate.	High.	Moderate.
Force Output	Low (μN range).	High (mN range).	Moderate (μN–mN).	Moderate to high.	High.
Speed of Actuation	High.	Moderate.	Very high.	Moderate.	Slow.
Precision	Moderate.	Low to moderate.	Very high.	Low.	Low.
Holding Capability	Strong for static loads.	Strong but temperature dependent.	Excellent, with minimal deformation.	Moderate, limited by field control.	Moderate.
Power	Low.	Moderate.	High	Moderate.	High.
Control and Stopping	Requires high-precision voltage control.	Thermal hysteresis may affect stopping accuracy.	Excellent; allows precise motion control.	Requires advanced field control.	Slower and requires temperature control.
Touching Impact	Low, but lacks precise modulation in aqueous environments.	High impact due to strong gripping force and thermal effects.	Very low; gentle, precise, and adjustable for delicate cells.	Moderate impact; less suited for precise applications.	High impact, difficult to modulate forces.
Suitability for Bio Cell Manipulation	Limited for wet applications; suitable for dry environments.	Suitable for tough cells; requires thermal management.	Excellent for delicate cell manipulation.	Limited by poor control in precise tasks.	Limited for delicate cell applications.
Energy Efficiency	High.	Moderate.	Moderate to high.	Moderate.	Low.

Piezoelectric actuation is chosen as the most compatible actuation method for the application due to that offering precise and gentle motion control, minimum touching impact to avoid cell damage, ensuring dynamic force adjustments, fast response and MEMS compatibility.

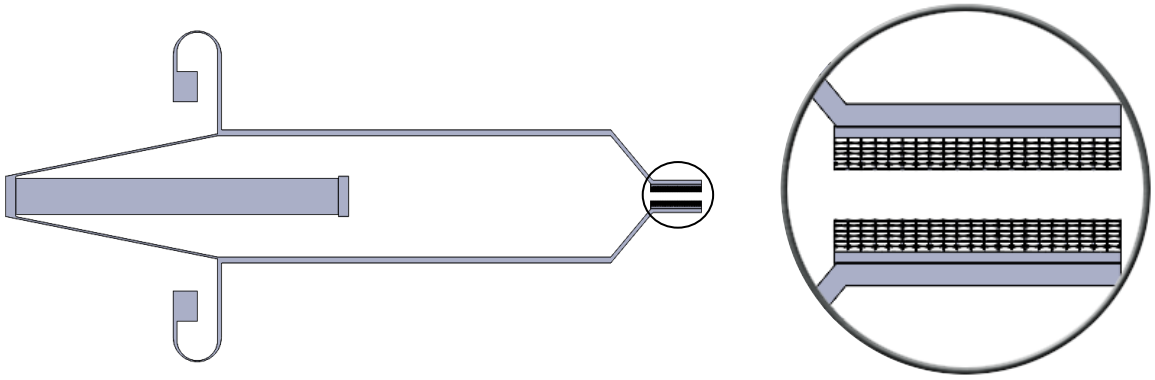
Sensing Method

Criterion	Piezoresistive	Capacitive	Optical	Piezoelectric	Resistive Strain Gauge
Sensitivity	Moderate	High	Very high	High	Low to moderate
Resolution	Moderate	High	high	High	Moderate
Integration with MEMS	Excellent; compact and easy to integrate	Excellent; widely used in MEMS designs	Poor; bulky and requires alignment	Good; requires specialized fabrication	Good; straightforward integration
Environmental Noise	Susceptible to thermal noise	Susceptible to electrical noise in wet environments	Immune to electrical and thermal noise	Minimal interference; stable in various conditions	Moderate; depends on material and design
Dynamic Response	Moderate	Moderate; not ideal for high-speed dynamics	Moderate; limited by system complexity	Excellent; suitable for rapid changes	Low to moderate
Cost	Low	Moderate	High	Moderate to high	Low
Power Consumption	Low	Moderate	Moderate to high	Moderate	Low
Real-Time Feedback	Good, with moderate delay	Excellent, supports rapid adjustments	Limited by bulk and complexity	Excellent; very fast response times	Moderate; slower than other methods
Suitability for Bio Cell Manipulation	Good for basic applications	Excellent; provides real-time control	Limited; bulky for MEMS and bio tasks	Excellent; precise force sensing in dynamic tasks	Moderate; suitable for larger force ranges

Capacitive sensing is chosen for its high sensitivity, excellent resolution, and seamless integration with MEMS. It provides precise force measurements at the nanoNewton level, making it ideal for real-time adjustments in biological cell manipulation.

4.2 Initial design

The conceptualization of a MEMS-based microgripper design for manipulating biological cells within the range of 10-100 microns was first conceptualized as follows. The two major parts of the gripper are piezoelectric actuators with high precision in displacements, which can safely and controlledly grip biological cells without causing damage, and capacitive sensors for force sensing using a highly deformable tip surface.



4.3 Actuation design

Design considerations

The microgripper aims at the manipulation of biological cells, whose diameters range from 10 to 100 microns. The design for the jaws of the gripper must be such that it accommodates the smallest and largest cell sizes with sufficient grip for reliable manipulation. Considering misalignment or flexibility during operation, the design is incorporating a jaw opening range of approximately 110 µm, including an additional tolerance of 10 µm.

Piezoelectric behaviour

Piezoelectric materials exhibit unique behaviour where mechanical deformation generates an electrical charge, and conversely, an applied electric field induces mechanical strain.

If the piezoelectric element is actuated along its length (L), the displacement (ΔL) is given by:

$$\Delta L = d_{33}.E.L$$

where:

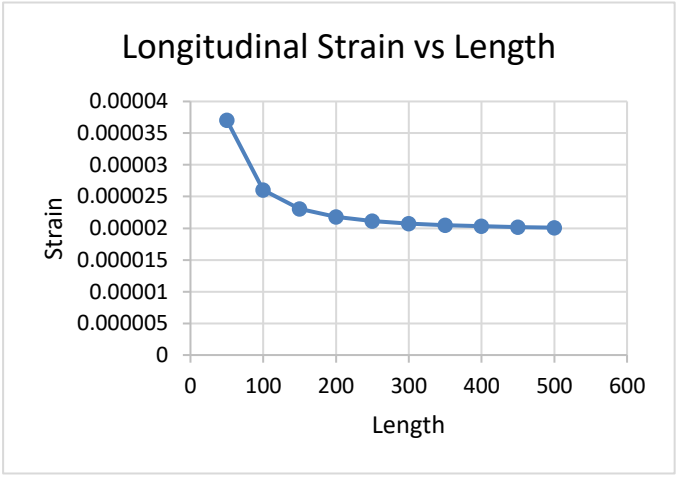
d33: Longitudinal piezoelectric coefficient.

E: Applied electric field.

L: Length of the piezoelectric material.

Experiment data for the displacement of the piezoelectric bat varying the length

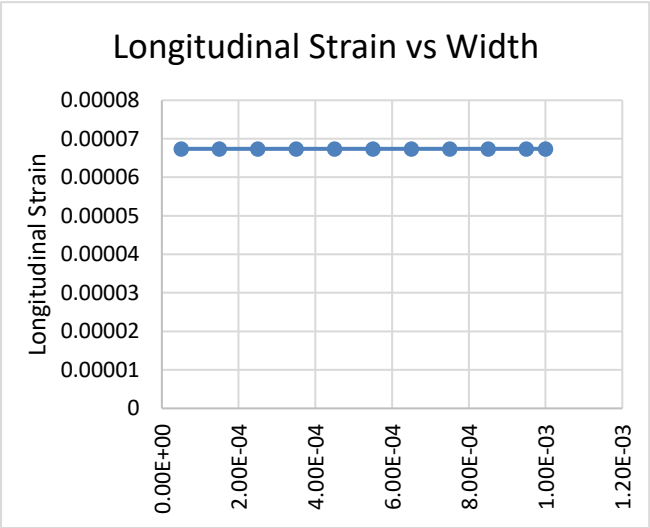
Length (μm)	Displacement	strain
50	0.001852	0.00003704
100	0.002605	2.6049E-05
150	0.003459	2.3062E-05
200	0.004359	2.1795E-05
250	0.005283	2.1132E-05
300	0.006221	2.0738E-05
350	0.007169	2.0484E-05
400	0.008124	2.031E-05
450	0.009083	2.0184E-05
500	0.010046	2.0092E-05



Shorter piezoelectric elements generate larger strains due to their smaller dimensions, allowing for higher strain per unit length. By stacking multiple piezoelectric elements, the total displacement is amplified, making piezoelectric stacks highly suitable for applications requiring larger displacements.

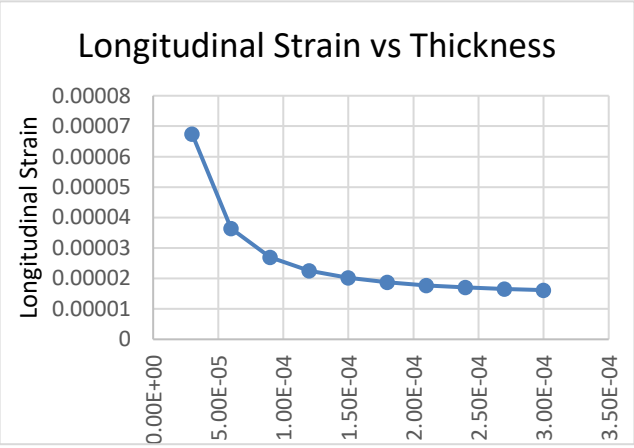
However, the width, W, has an indirect influence on the displacement whereby wider materials disperse the strain across a greater area that reduces the mechanical stability while simultaneously minimizing strain concentration.

Width (μm)	Longitudinal Displacement	Strain
5.00E-05	0.006739	0.000067388
1.50E-04	0.006739	0.000067388
2.50E-04	0.006739	0.000067388
3.50E-04	0.006739	0.000067388
4.50E-04	0.006739	0.000067388
5.50E-04	0.006739	0.000067388
6.50E-04	0.006739	0.000067388
7.50E-04	0.006739	0.000067388
8.50E-04	0.006739	0.000067388
9.50E-04	0.006739	0.000067388
0.001	0.006739	0.000067388



The electric field (E=V/T), which is inversely proportional to the thickness (T), significantly affects the longitudinal deformation (ΔL) in piezoelectric materials.

Thickness (μm)	Longitudinal Displacement	Longitudinal Strain
3.00E-05	0.006739	0.000067388
6.00E-05	0.003642	0.000036416
9.00E-05	0.002691	0.00002691
1.20E-04	0.002256	0.000022562
1.50E-04	0.002017	0.000020169
1.80E-04	0.00187	0.000018698
2.10E-04	0.001772	0.000017723
2.40E-04	0.001704	0.000017041
2.70E-04	0.001654	0.000016543
3.00E-04	0.001617	0.000016167

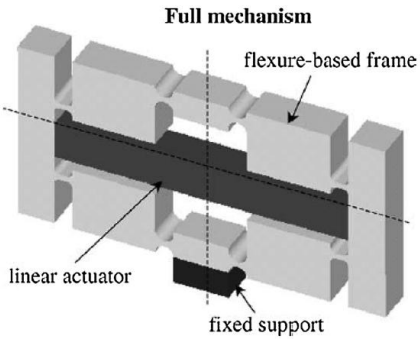


A smaller thickness amplifies the electric field (E=V/T), increasing displacement while thicker materials reduce the electric field and hence the displacement.

Since a typical displacement for a single piezoelectric element does not exceed 1-2 μm, realization of a required jaw displacement of 55-60 μm requires amplification mechanisms. There are common amplification mechanisms as follows

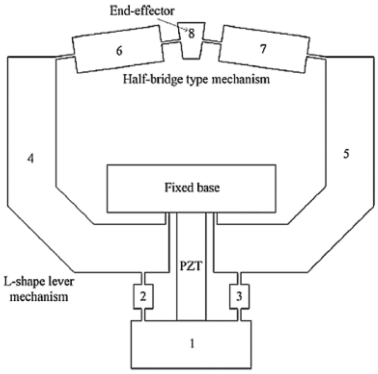
Bridge-type mechanism

The bridge-type mechanism of amplification couples the micro-flexures and the micro-hinges for amplifying input displacement. Their amplification factor depends upon the flexure dimensions, type of hinge used, and geometric properties. This realizes a compact size with a high amplification ratio, thereby making these devices suitable for micro-actuators. In such cases, flexure hinges, of single-axis and circular type, increase the performance at the expense of stress concentrations resulting in brittleness or cracking. Its design has been refined through the use of elastic beam theory, kinematic principles, and FEM simulations. Improved designs were created through better analysis models on the amplification ratio and distribution of stiffness. Due to the high gain in displacement, de-amplification in force and a very small lateral stiffness need special care during structural optimization.



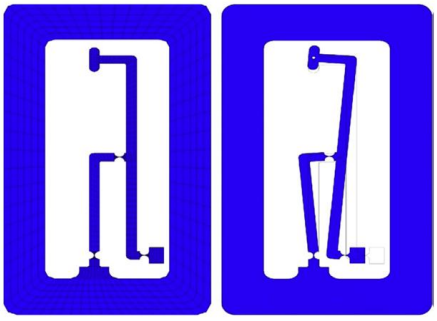
Lever and Bridge-type mechanism

L-shaped levers combined with a bridge structure serve for the effective amplification of the piezoelectric actuator displacement. The leverage mechanism gives the preliminary amplification of displacement, and the bridge mechanism amplifies the stroke. Hence, this configuration becomes ideal for applications requiring high amplification in compact design form. The hybrid nature combines the merits of large displacement output and structural efficiency effectively.



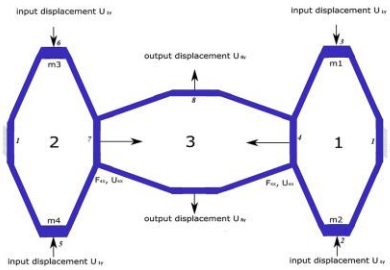
Scott–Russell mechanism

SCOTT-RUSSELL is the flexure-based displacement amplification mechanism used for nano-manipulation. Driven by a piezo-actuator, this gives higher mechanical output: while allowing amplification factor increase, it develops high displacements and velocities.



Multi-stage force displacement amplification mechanism

The multi-stage force displacement amplification mechanism was developed to enhance the efficiency of piezoelectric systems by the progressive amplification of input forces or displacements. It takes advantage of elastic beams and a flex-compressive center for dynamic transfer and amplification of forces. This, in turn, overcomes the limitation inherent in piezoceramics, having high stress capacity with low strain, through the distribution of forces across multiple amplification stages. This mechanism thus offers very good performance when applied in those situations that require large displacements or power generation.

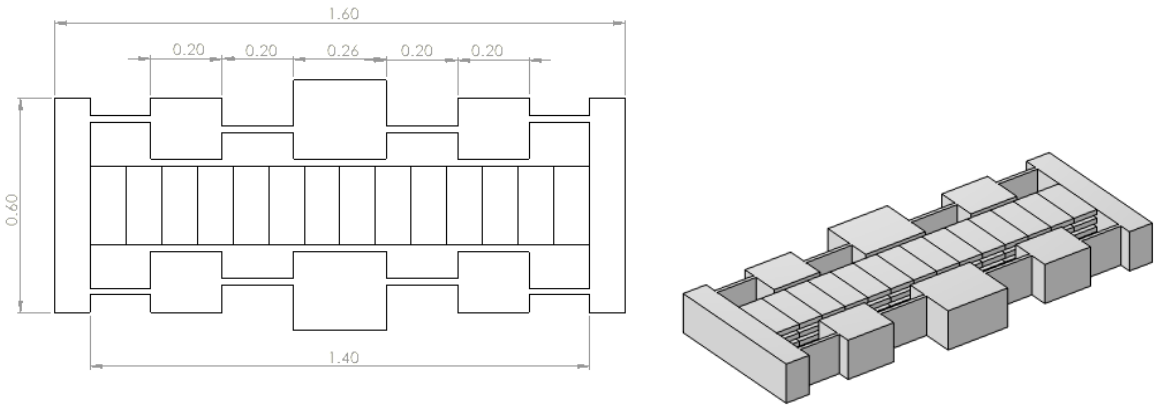


The Bridge Amplifier with Flexural Hinges mechanism is chosen for its ability to amplify piezoelectric displacement effectively. By combining multiple levers and compliant flexural elements, it enables smooth rotational motion, translating small piezoelectric displacements into larger outputs. Its compact design ensures easy integration into MEMS devices while evenly distributing forces across the structure, reducing stress concentrations and enhancing durability.

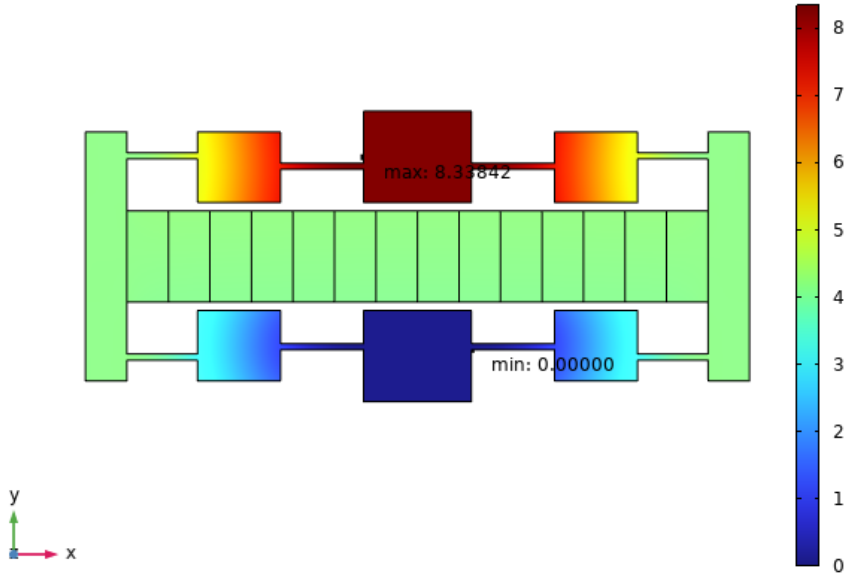
Despite the advantages, the mechanism has some drawbacks; more specifically, the cumbersome making process of the mechanism involves some intricate alignments, along with a high precision make that ensures its structural integrity while maintaining a displacement of 55–60 µm. The mechanism due to its effectiveness and robustness is, however, one of the finest options regarding microgripper operations.

Final Design of the Bridge Amplifier

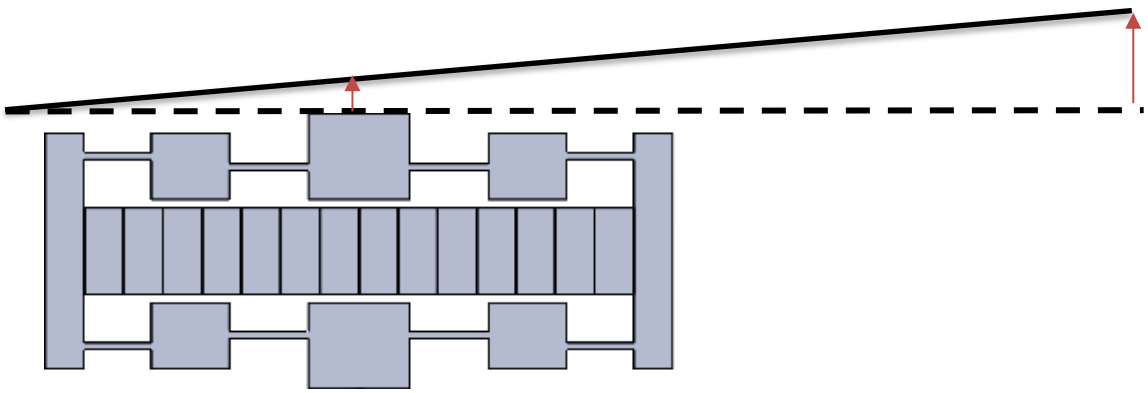
The best Bridge Amplifier Design has 14 piezoelectric elements in 5 layers across, each of length 100 µm and thickness 20 µm. This is optimally configured for higher displacements and forces with better structural integrity and strain distribution. The use of multiple layers within this design dramatically enhances amplification efficiency, with the resulting total displacement being approximately 8 µm.



Volume: Displacement magnitude (μm) Max/Min Volume: Displacement magnitude (μm)

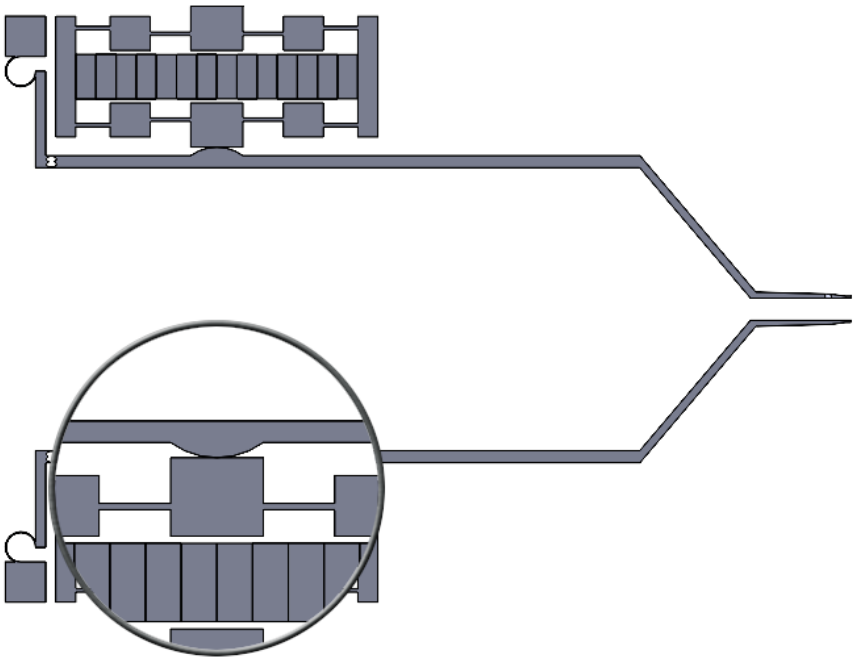


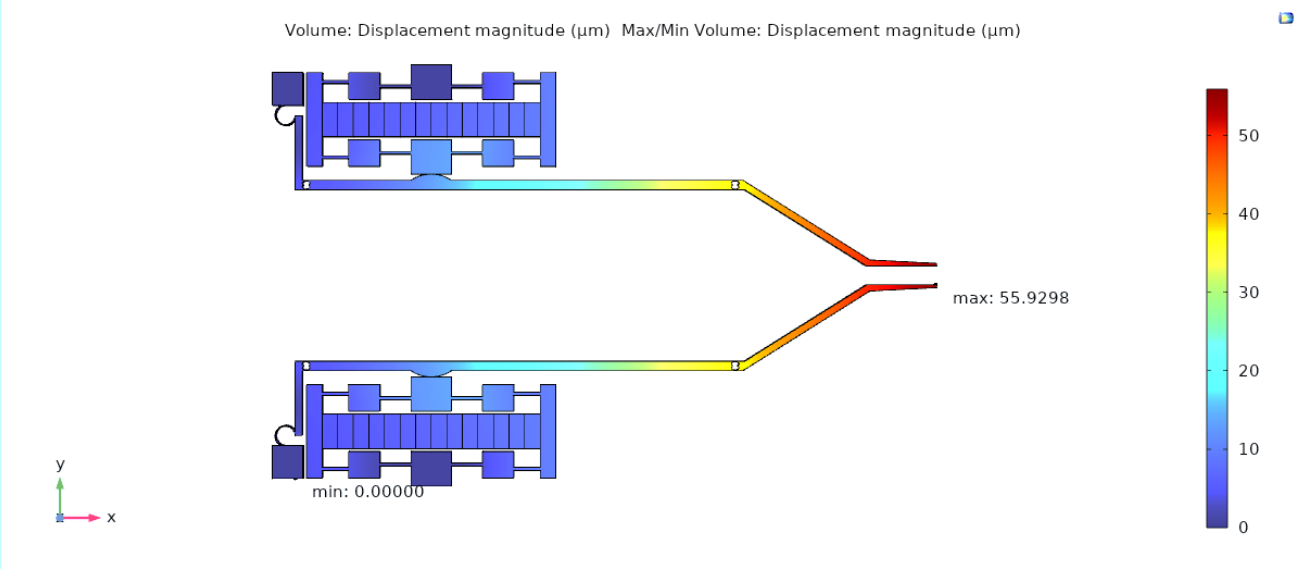
Designing the gripper jaw



$$\frac{0.5 \times bridge\ length}{Arm\ length} = \frac{8}{55} \quad \rightarrow \quad Arm\ length = 0.5 \times 1600 \times \frac{55}{8} = 5500\ \mu m$$

To achieve the required 55–60 µm deflection per jaw with an 8 µm amplified displacement, a compliant hinge (flexure) mechanism is utilized instead of traditional joints. Flexures provide smoother motion and reduced wear, optimizing performance. The arm length is reduced from 5500 µm to 4000 µm, ensuring compactness while maintaining the necessary deflection through efficient hinge design. The final design according to these criteria is as follows.



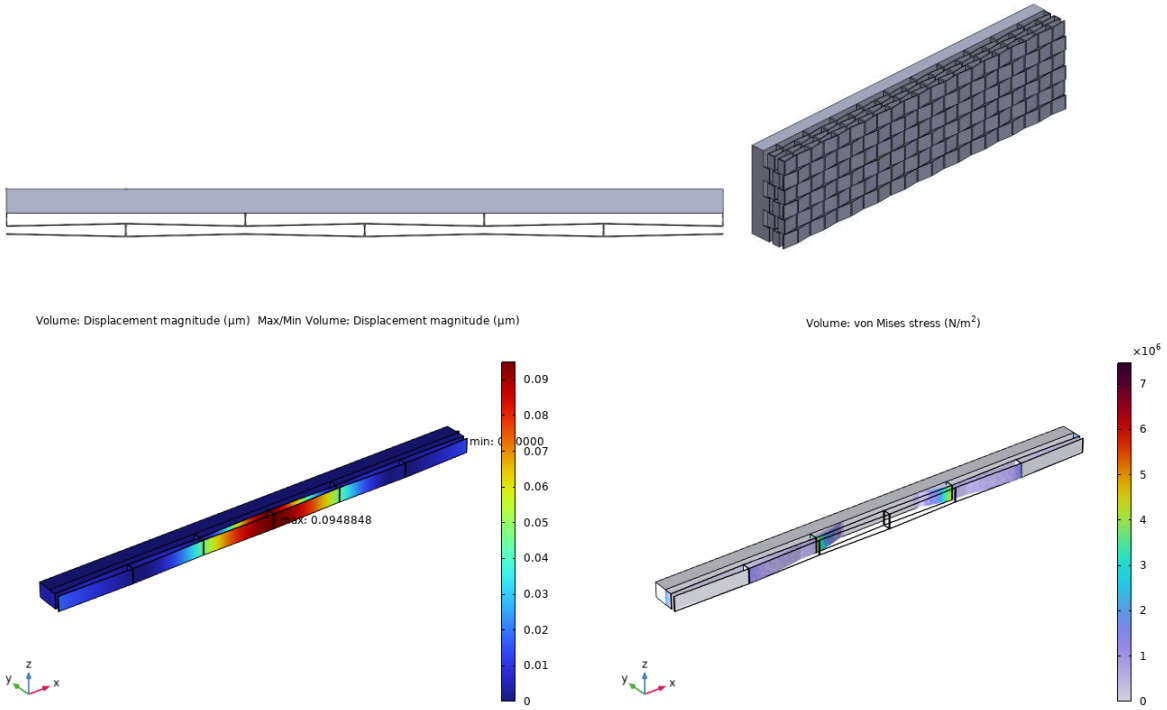


4.3.1 Sensing Design

Capacitive sensing is selected due to its high sensitivity and compatibility with the MEMS fabrication techniques. The mechanism measures the deflection of the gripper tip surface, which corresponds to the applied force during cell manipulation.

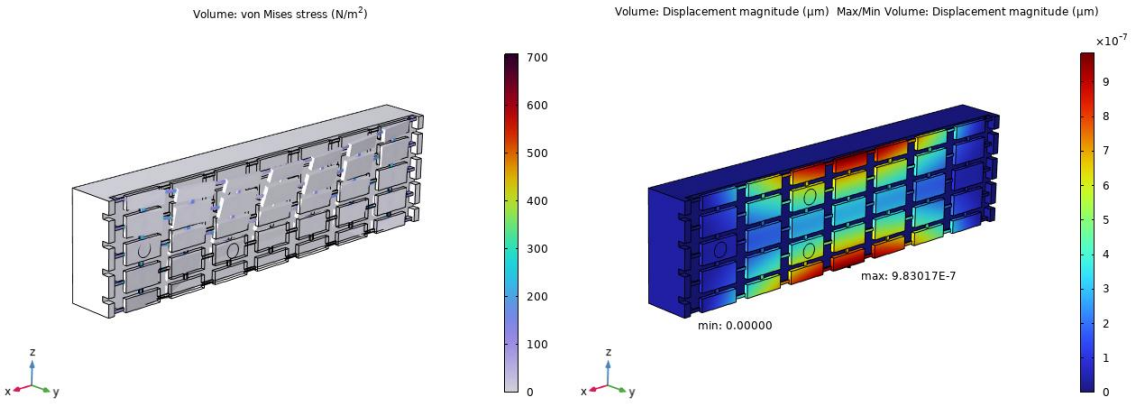
Capacitive plates are strategically placed next to the gripper tips, so that changes in the distance between them result from the deflection of the tips and thus result in a change in capacitance. This allows for instant feedback to dynamically control the applied force. The sensing system is calibrated to measure forces ranging from 10 nN to 1 µN, thus ensuring that the pressure is maintained below the maximum limit tolerated by biological cells. The tip surface is geometrically designed to control the deformation to be highly sensitive to tiny displacements.

Surface design 1:



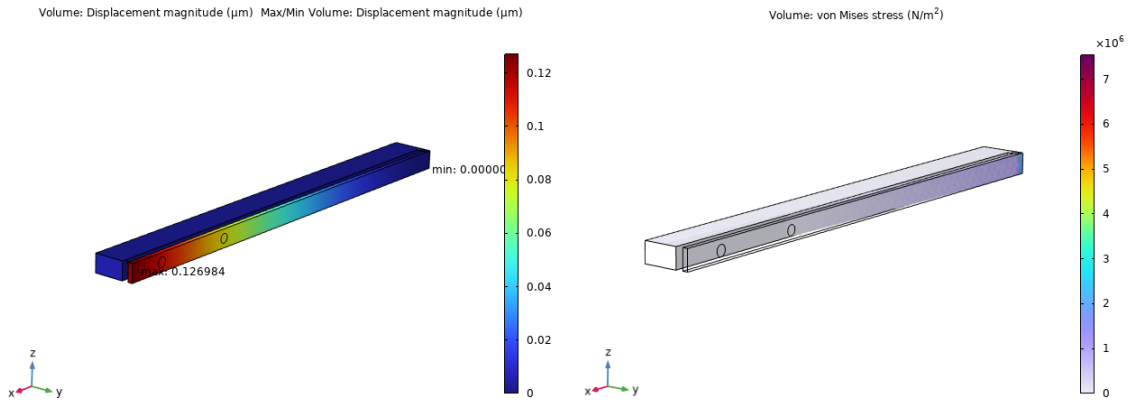
Surface Design 1 has good deformation characteristics, but it suffers from a very high aspect ratio, which reduces the manufacturability of the structure in practice. The complex geometry also affects the manufacturability, therefore increasing the risk of defects in the MEMS fabrication process. Moreover, the design may have inferior structural stability, especially under cyclic loading conditions, and might be prone to mechanical failure due to stress concentrations at sharp edges or slender regions.

Surface Design 2:



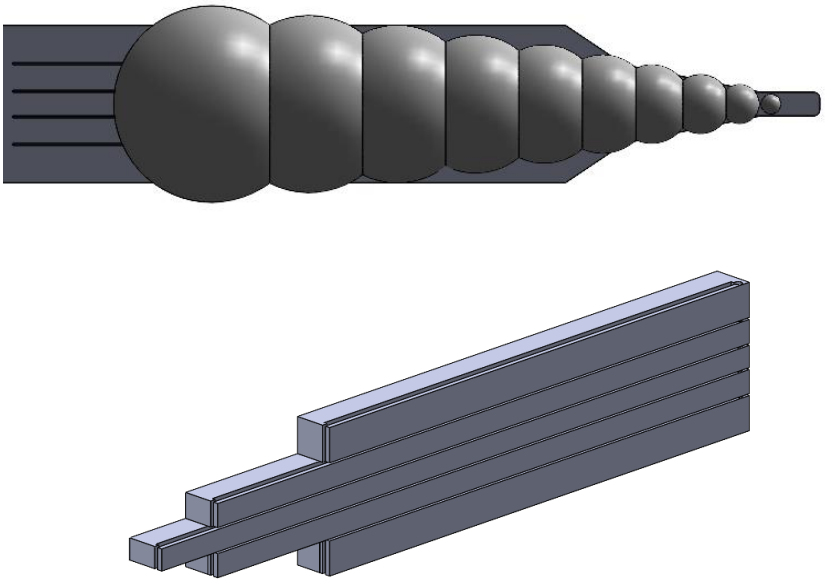
Surface Design 2 has a simple geometrical setup, which allows for good manufacturability. However, while it exhibits less deflection, it is still not good enough for applications where precise and significant movement is required. Another drawback is that when this structure is under gravitational forces, it deforms unwelcomely, thus losing in precision and reliability. This design can also be subject to uneven distribution of stresses, leading to localized weaknesses and reduced overall strength.

Surface Design 3:



Surface Design 3 is a typical cantilever design with small patterns and, hence, balances between practical functionality and ease of manufacture. It allows large deflection while meeting all the requirements of precise motion detection and force measurement. Its good manufacturability ensures easy fabrication processes, even with the use of MEMS. The design also exhibits increased stability, reducing deformation caused by gravitational loads or external pressures and, hence, ensuring stable performance during operation.

Design of the tip and surface



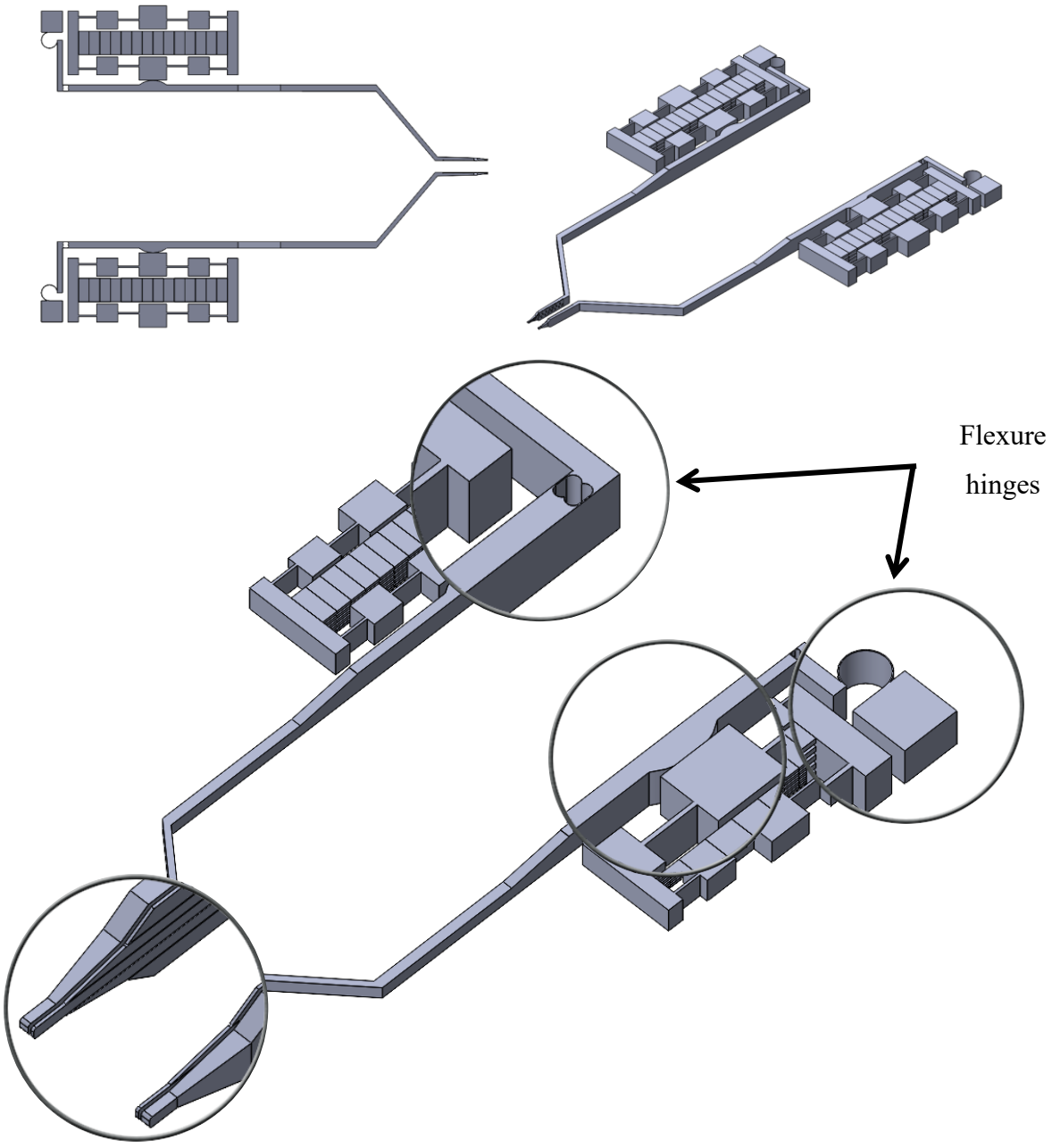
The tip and tip surface are designed to safely handle biological cells ranging from 10 to 100 μm in diameter with features to reduce damage but still provide a secure grip. In an effort to reduce pressure points and increase contact area to protect delicate cells, gripping tips are coated with a soft polymer such as PDMS.

The tip surface is fabricated with micro-textures, such as microgrooves or dimples, using photolithography or laser micromachining to increase the friction and grip without applying large forces. The tip geometry is optimized with rounded or concave shapes to evenly distribute stress and gently envelop the cell.

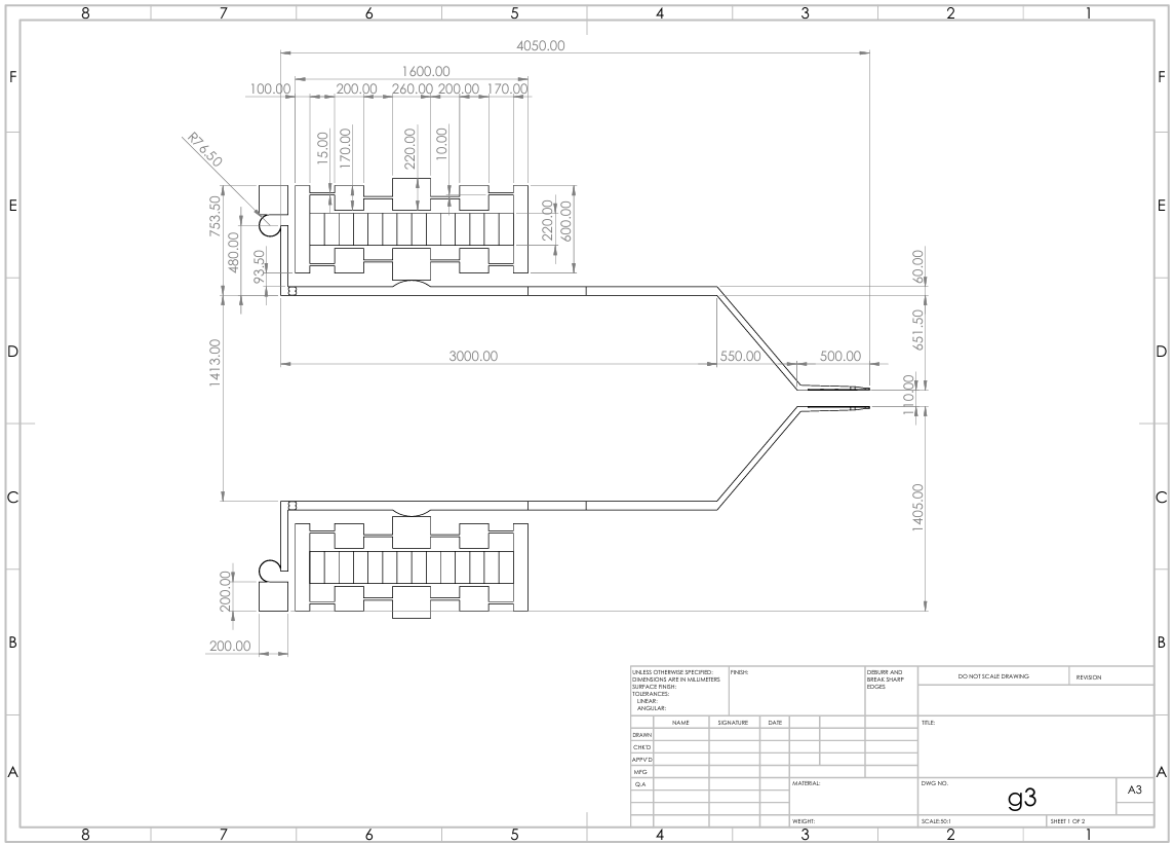
Additional enhancements include biocompatible coatings like silicone or hydrogel to improve grip and reduce the risk of damage, and anti-adhesion layers (e.g., PEG) to prevent cell sticking. These design features ensure precise, adaptable, and safe cell manipulation for the intended application.

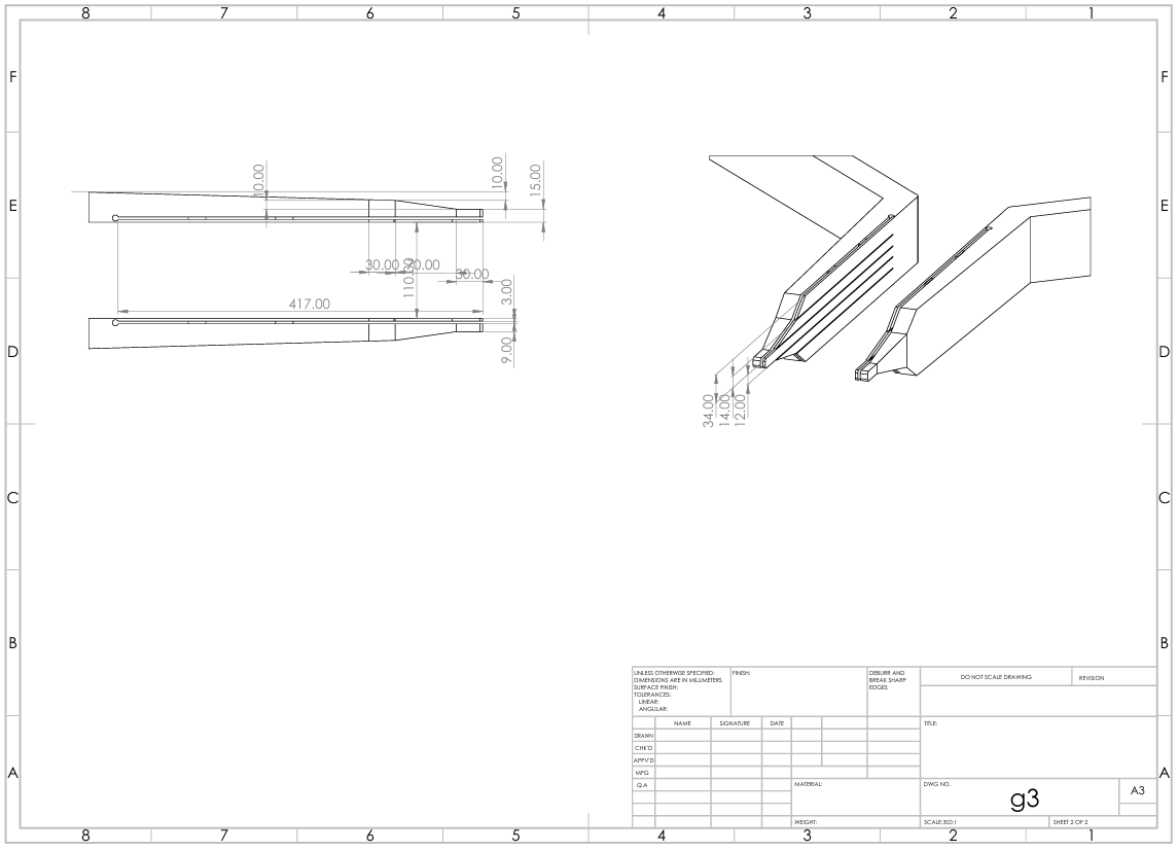
Final design of the microgripper

3D Model of the structure



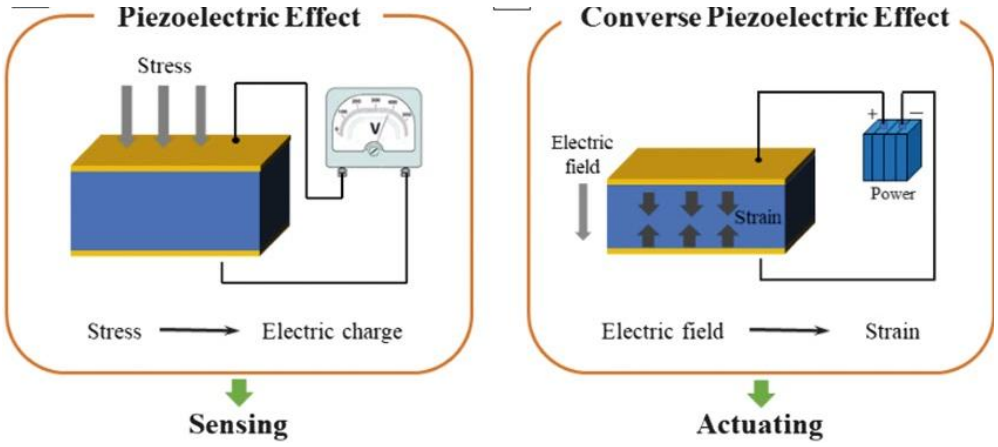
Detailed Drawing





5 WORKING PRINCIPLE

Actuation



The piezoelectric effect is a reversible electromechanical phenomenon where mechanical strain generates an electric charge (direct effect) or an applied electric field induces mechanical deformation (inverse effect). This property is leveraged for precise actuation in MEMS microgrippers.

Piezoelectric materials operate in two primary modes:

1. d33 Mode (Longitudinal Effect)
2. d31 Mode (Transverse Effect)

For the microgripper, longitudinal displacement is utilized to achieve the required actuation. When an electric field is applied, mechanical deformation is induced, which is proportional to the field strength and the piezoelectric coefficient d33. The displacement can be calculated as:

$$\Delta L = d_{33} \cdot \frac{V}{T} \cdot L$$

Where:

- ΔL: Longitudinal displacement,
- L: Length of the actuator,
- T: Thickness of the piezoelectric material,
- V: Applied voltage.

Sensing

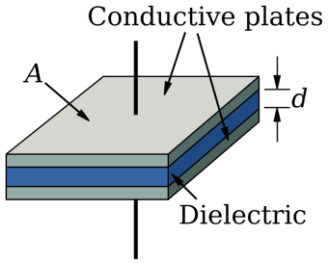
Capacitive sensing is selected for its high sensitivity and compatibility with MEMS fabrication techniques, making it ideal for detecting minute displacements in the micro-scale range due to the applied force during cell manipulation.

The capacitive sensing system is calibrated to measure forces in the range of 10 nN to 1 μN, corresponding to the maximum bearable pressure for a biological cell. The measured deflection is used to calculate the applied force based on the mechanical properties of the gripper structure:

$$F = k \cdot \Delta d$$

The capacitance (C) between two parallel plates is given by:

$$C = \epsilon . \frac{A}{d}$$



Where:

- ϵ: Permittivity of the dielectric medium,
- A: Overlapping area of the plates,
- d: Initial gap between the plates.

When the gripper tip deflects by a small distance (Δd), the gap changes to (d+Δd), resulting in a change in capacitance (ΔC):

$$\Delta C = \frac{\epsilon . A}{d + \Delta d} + \frac{\epsilon . A}{d}$$

For small deflections (Δd≪d), the capacitance change can be approximated as:

$$\Delta C \approx \frac{\epsilon . A . \Delta d}{d^2}$$

The sensing system measures this capacitance change using a charge amplifier. The resulting signal is processed and converted into a displacement value.

6 MATERIAL SELECTION

Jaw Arms

The jaw arms require high stiffness to efficiently transmit amplified displacement, low mass to reduce gravitational deformation, and compatibility with MEMS fabrication processes such as etching or deposition. These properties ensure precision and stability during operation.

Material Options:

- Silicon
- Polysilicon
- Silicon Nitride (Si_3N_4):

Properties of Silicon

Property	Va	Value
Young's modulus	E	170e9[Pa]
Thermal conductivity	k...	130[W/(m*K)]
Relative permittivity	e...	11.7
Poisson's ratio	nu	0.28
Heat capacity at constant pressure	C...	700[J/(kg*K)]
Density	r...	2329[kg/m^3]
Coefficient of thermal expansion	a...	2.6e-6[1/K]

Properties of Silicon Nitride

Property	Va	Value
Coefficient of thermal expansion	a...	2.3e-6[1/K]
Density	r...	3100[kg/m^3]
Electrical conductivity	s...	0[S/m]
Heat capacity at constant pressure	C...	700[J/(kg*K)]
Poisson's ratio	nu	0.23
Relative permittivity	e...	9.7
Thermal conductivity	k...	20[W/(m*K)]
Young's modulus	E	250e9[Pa]

Properties of Polysilicon

Property	Va	Value
Density	r...	2320[kg/m^3]
Young's modulus	E	160e9[Pa]
Poisson's ratio	nu	0.22
Coefficient of thermal expansion	a...	2.6e-6[1/K]
Heat capacity at constant pressure	C...	678[J/(kg*K)]
Relative permittivity	e...	4.5
Thermal conductivity	k...	34[W/(m*K)]

Silicon Nitride (Si_3N_4) is preferred for its balance of stiffness, toughness, wear resistance, and chemical stability, making it ideal for use in biological environments ensuing stable and reliable performance of the jaw arms while reducing wear and deformation risks.

Bridge Amplifier

The bridge amplifier requires high stiffness for efficient force transmission, high fatigue resistance to endure repeated actuation cycles, and lightweight properties to reduce overall system inertia. Flexural hinges must provide sufficient flexibility for smooth motion while maintaining durability under repeated stress. Additionally, stress concentration at flexure points should be minimized to enhance structural integrity.

Silicon is selected for its high stiffness, which ensures precise displacement amplification, and its seamless integration with MEMS fabrication processes. Its low density contributes to reducing the dynamic response time, making it an ideal choice for this application.

Piezoelectric Elements

The piezoelectric elements require high piezoelectric coefficients (d33d_{33}d33) for maximum actuation efficiency, good mechanical coupling with the bridge amplifier and jaws, and stability under applied electric fields and repeated actuation cycles. These properties are critical for achieving the precise motion needed in the microgripper.

Material options	Aluminum Nitride	Lead Zirconate Titanate	Zinc Oxide
d_{33}	5[pC/N]	289[pC/N]	11.67[pC/N]

PZT is chosen for its superior piezoelectric properties (d33=289 pC/N), ensuring sufficient actuation despite its brittleness. Its high efficiency makes it ideal for achieving the required displacement in the microgripper.

Tip Geometry

The tip geometry must be lightweight to minimize gravitational deformation, flexible yet durable to withstand repeated loading at the cantilever beams, and biocompatible to ensure safe interaction with biological cells. These requirements are critical for maintaining precision and reliability during cell manipulation.

Material Options: Polysilicon, PDMS (Polydimethylsiloxane), Silicon Nitride (Si_3N_4), Gold-Coated Silicon

Selected material:

1. Silicon Nitride (Si_3N_4) for the structural framework due to its mechanical strength, wear resistance, and stability.
2. PDMS Coating on the tip surface to enhance biocompatibility and reduce stress concentration on biological cells. This combination ensures precision and safe manipulation.

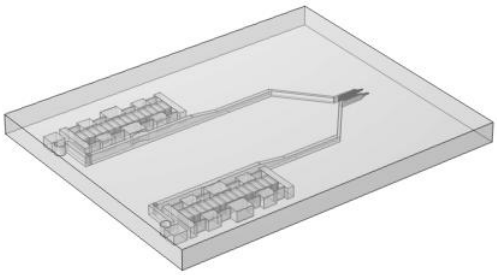
Material selection as conclusion

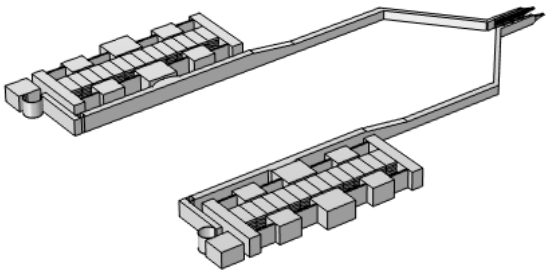
Component	**Selected Material**
Jaw Arms	Silicon Nitride
Bridge Amplifier	Silicon
Piezoelectric Elements	Lead Zirconate Titanate (PZT)
Tip Geometry	Silicon Nitride

7 SIMULATION AND RESULTS

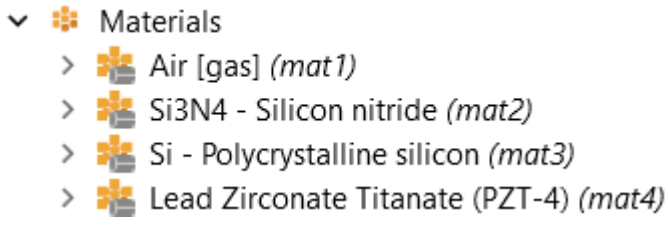
Importing 3D model and creating air domain

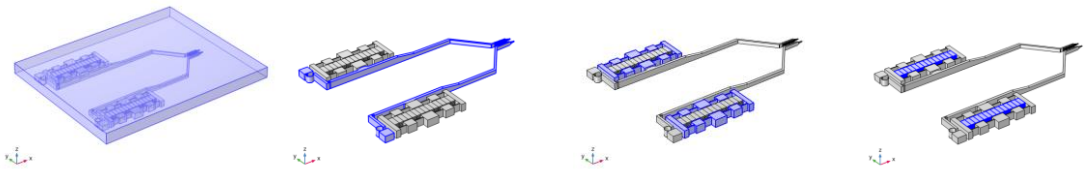
3D model is designed using SolidWorks and imported to COMSOL Multiphysics for simulating the microgripper



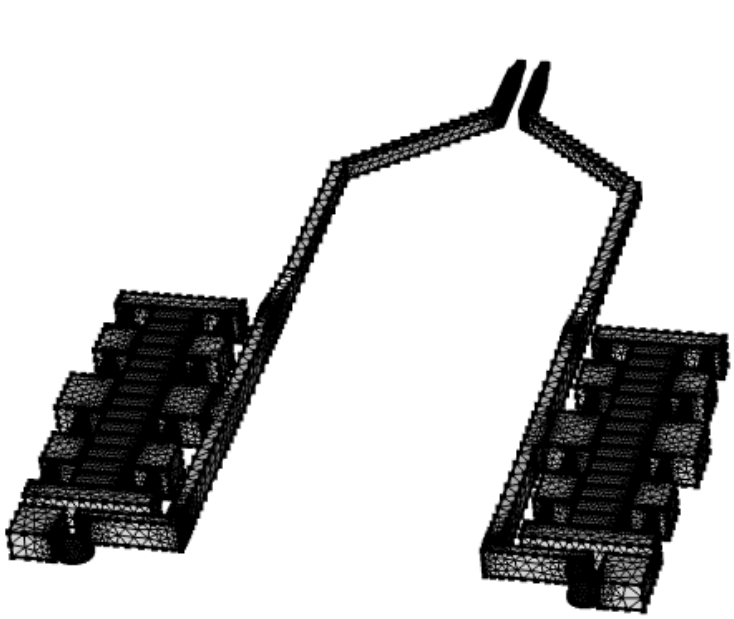


Material assignment





Meshing



Statistics

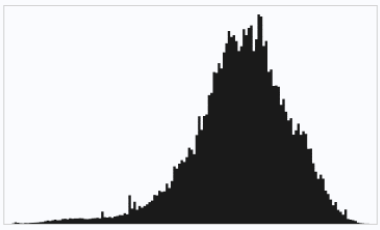
Complete mesh

Mesh vertices:	76371
Element type:	All elements
Tetrahedra:	443184
Triangles:	88694
Edge elements:	12655
Vertex elements:	1300

Domain element statistics

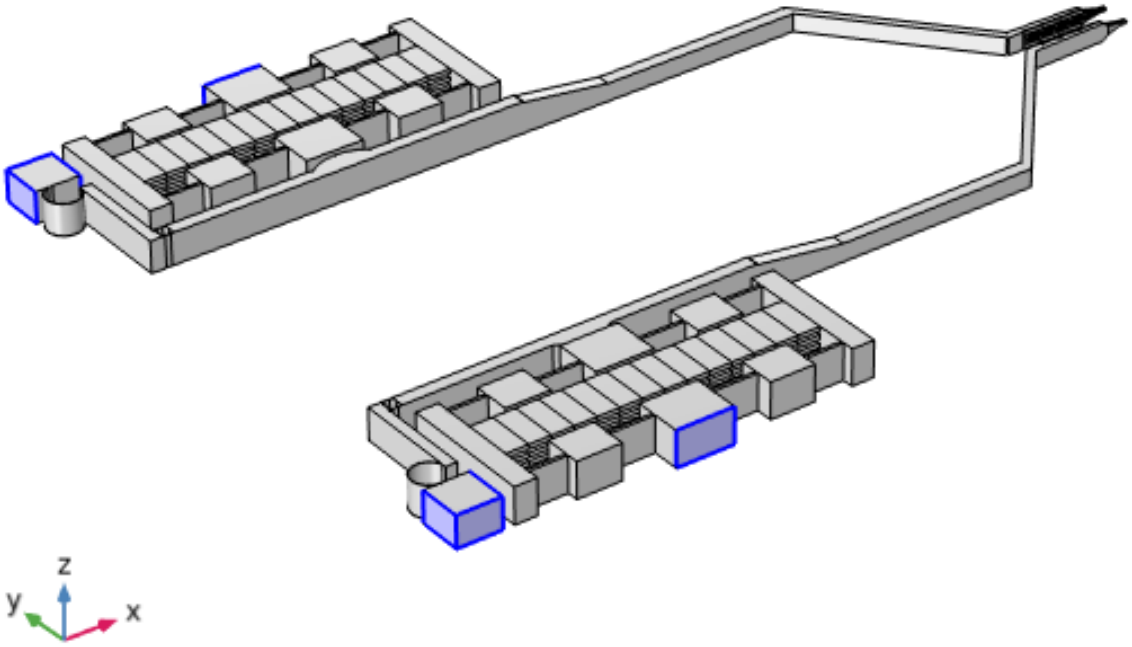
Number of elements:	443184
Minimum element quality:	0.01904
Average element quality:	0.6345
Element volume ratio:	2.969E-8
Mesh volume:	6.0E9 µm³

Element Quality Histogram



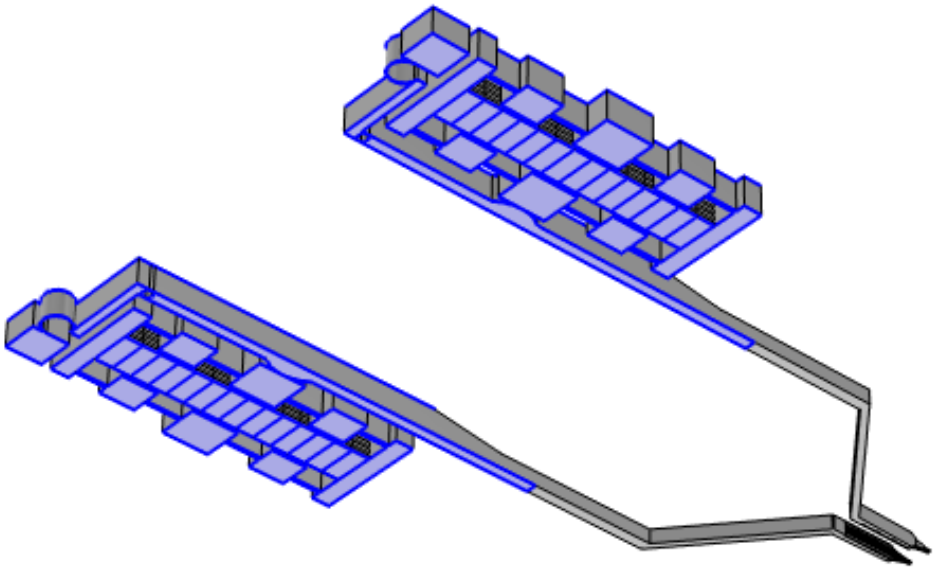
Fixed constraints

Fixed surface constraints were applied to the surfaces which are connected to the Si wafer



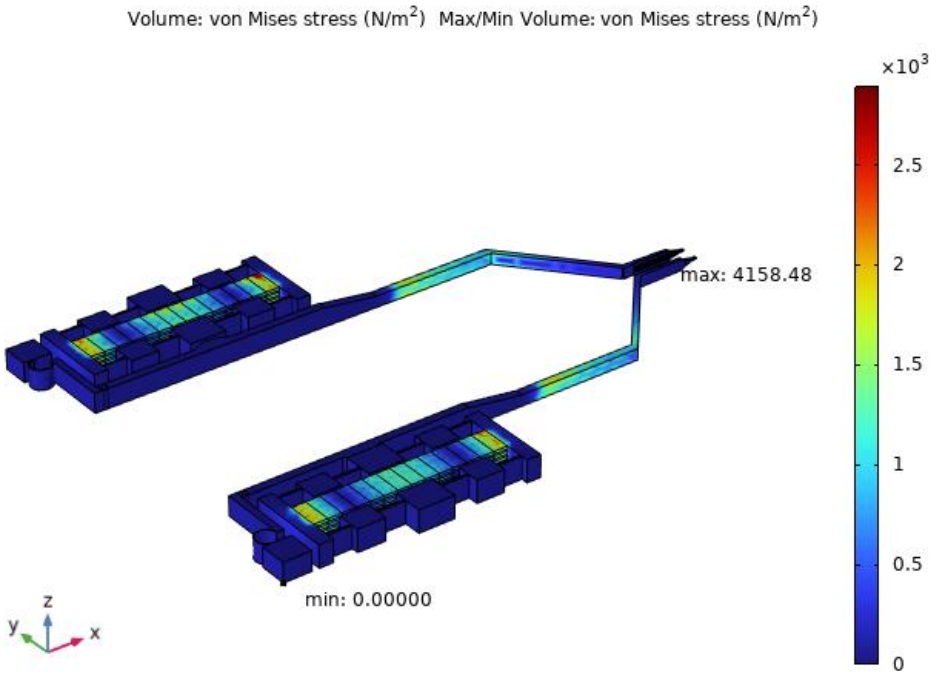
Roller constraints

Roller surface boundary conditions were employed to guide the movement of gripper on horizontal plane.

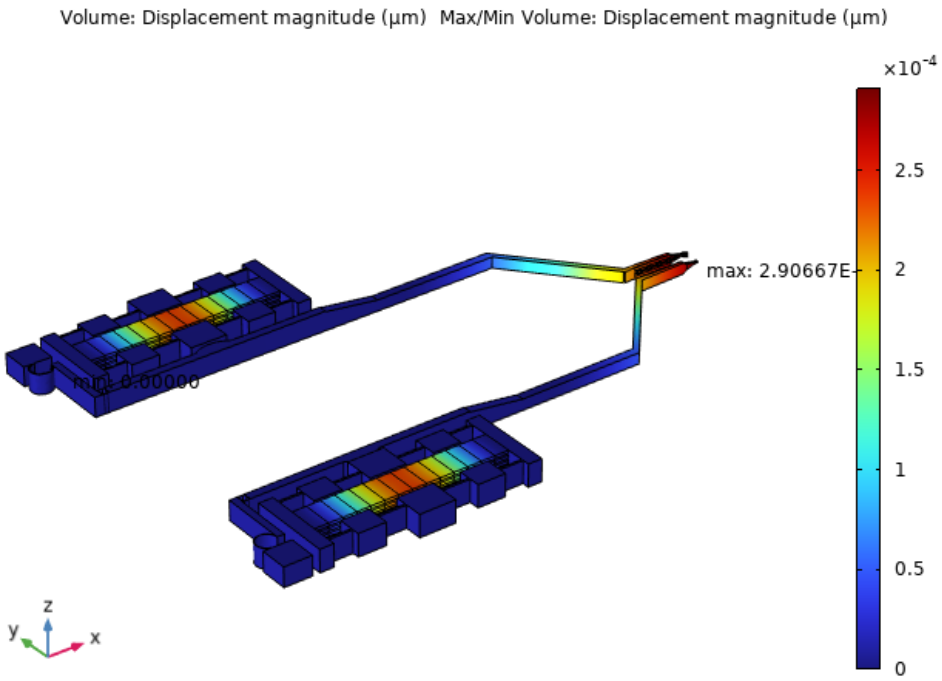


Structural stability under gravity without external force

Stress variation

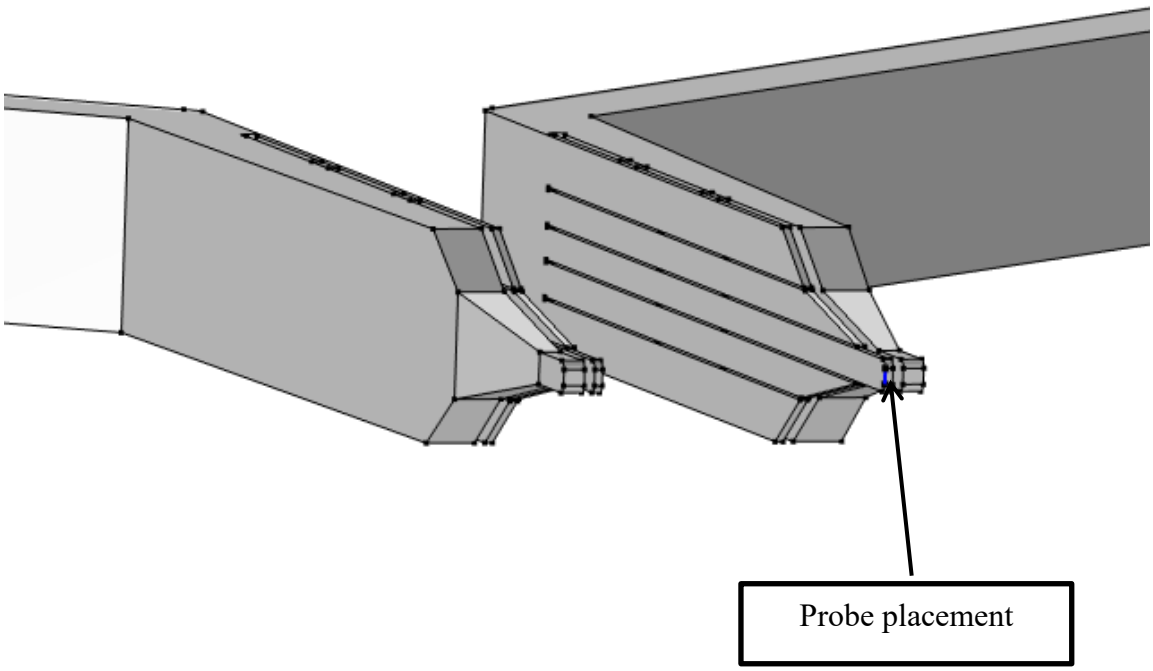


Deflection variation

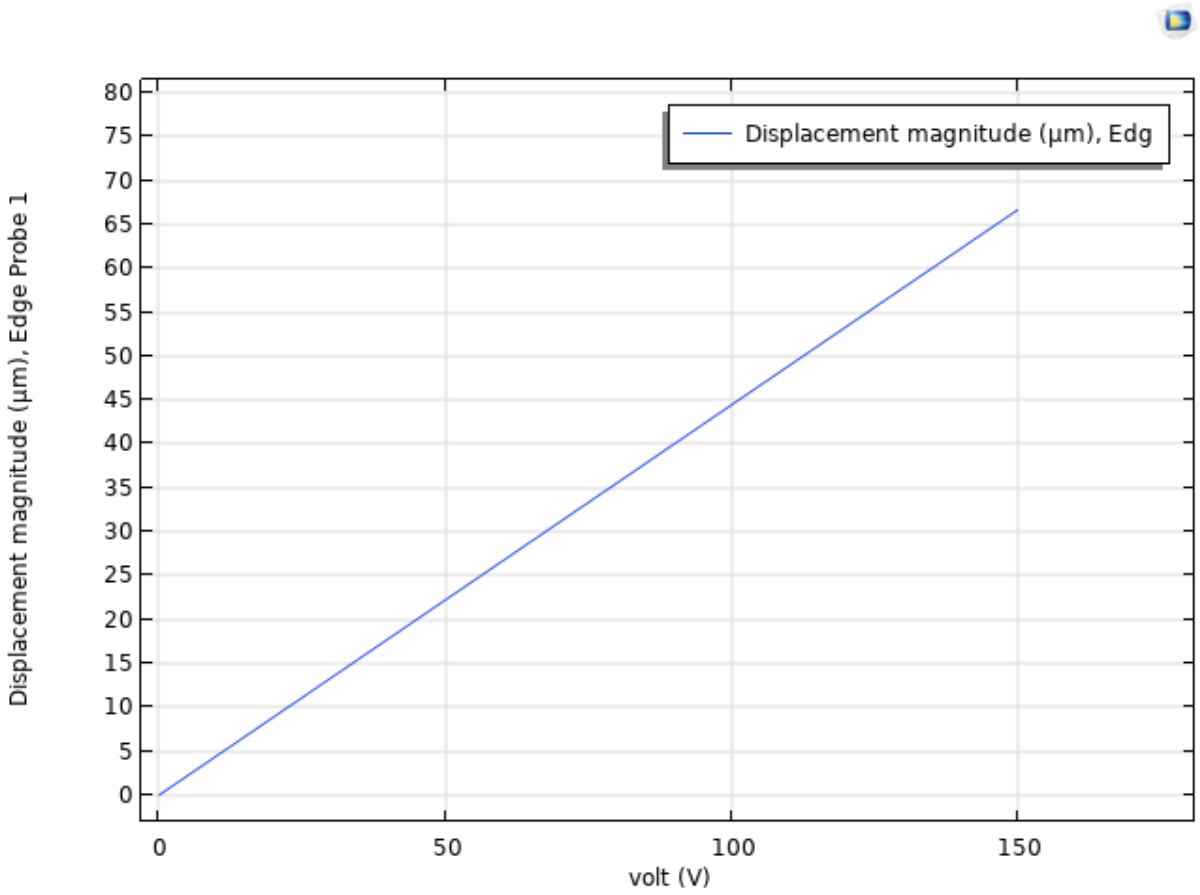


Actuation

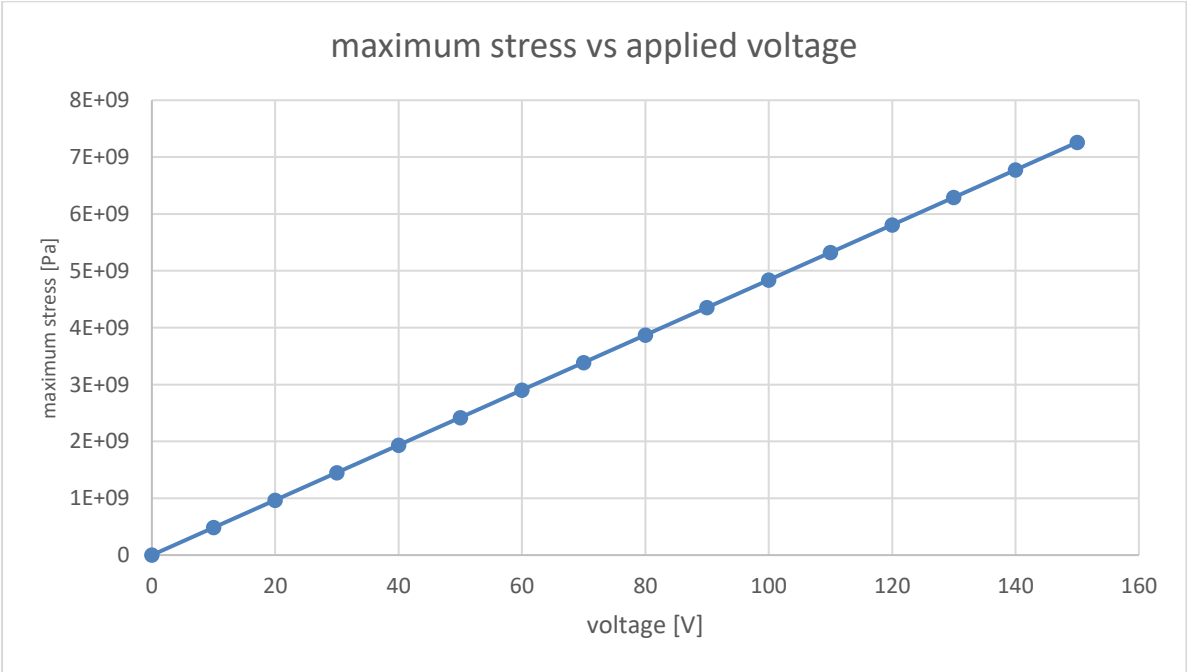
0 – 150 V varying voltage is applied for the piezoelectric elements and displacement of the tip is measured using a probe for the applied voltage.



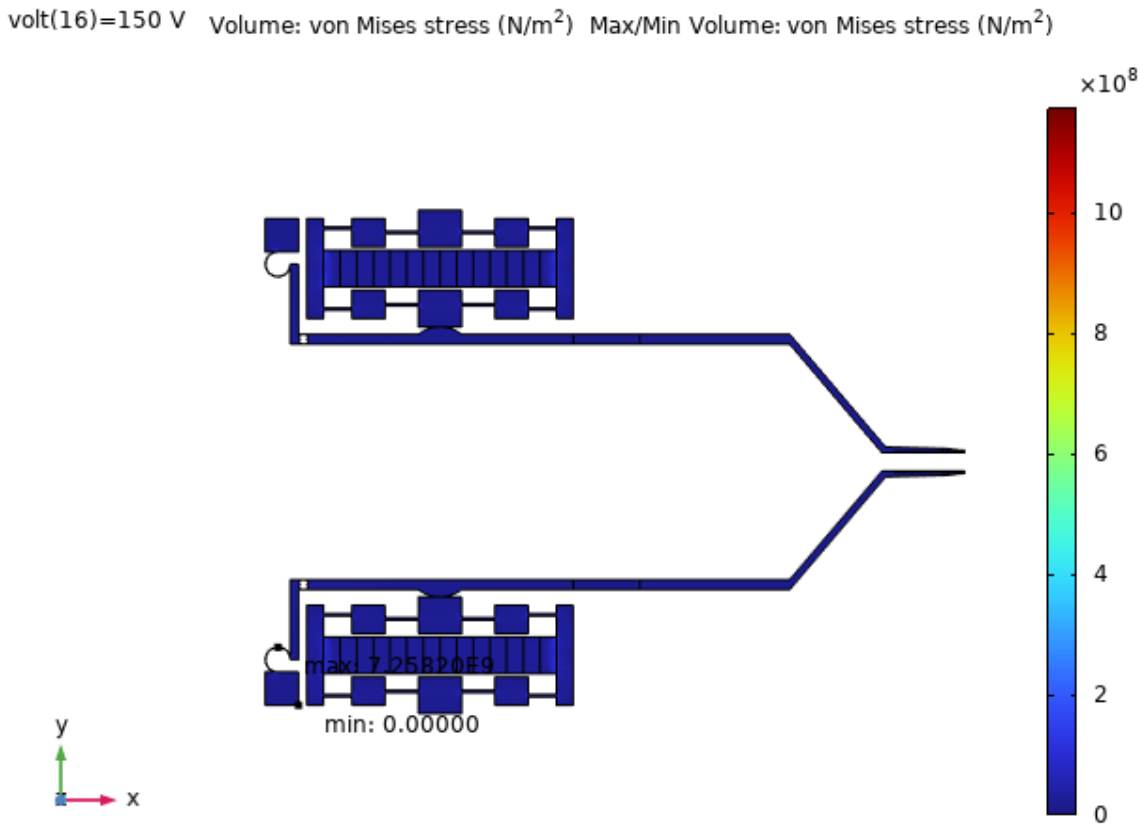
Displacement of the tip with respect to the applied voltage



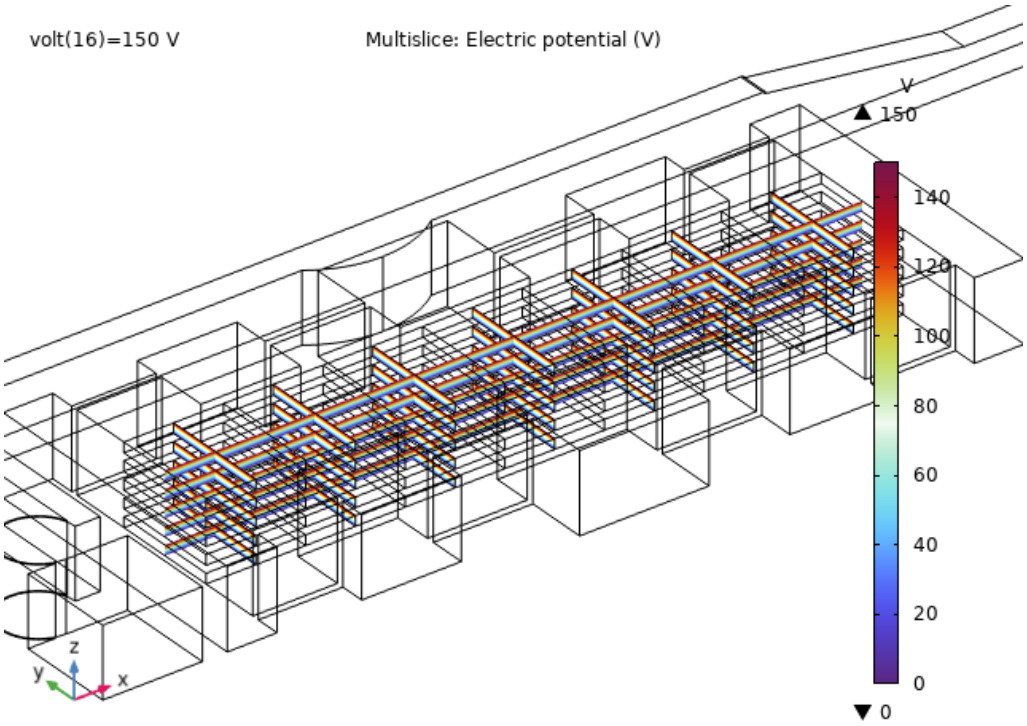
Maximum stress variation for applied voltage



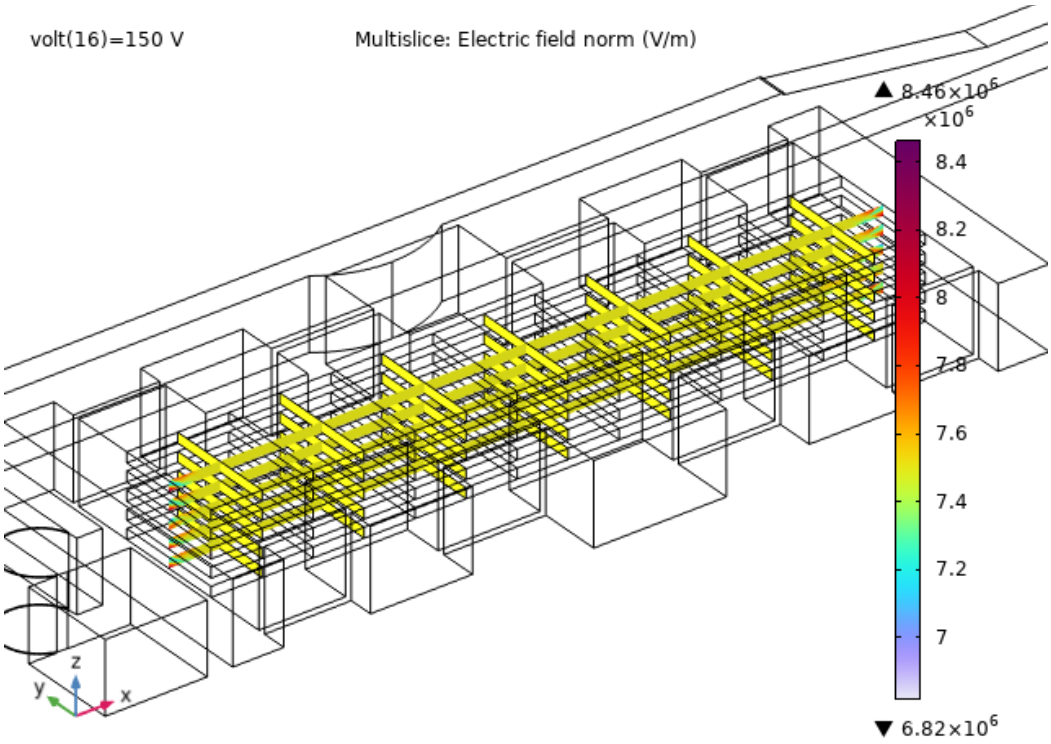
Stress variation at 150 V: (at maximum deflection)



Electric potential variation of the piezoelectric elements



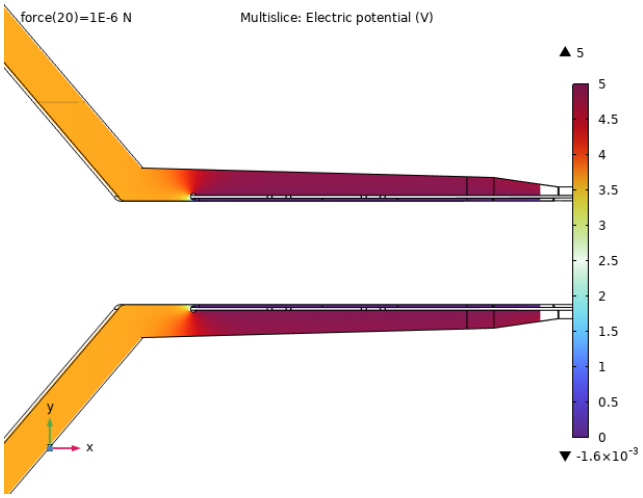
Electric field generated on the piezoelectric elements



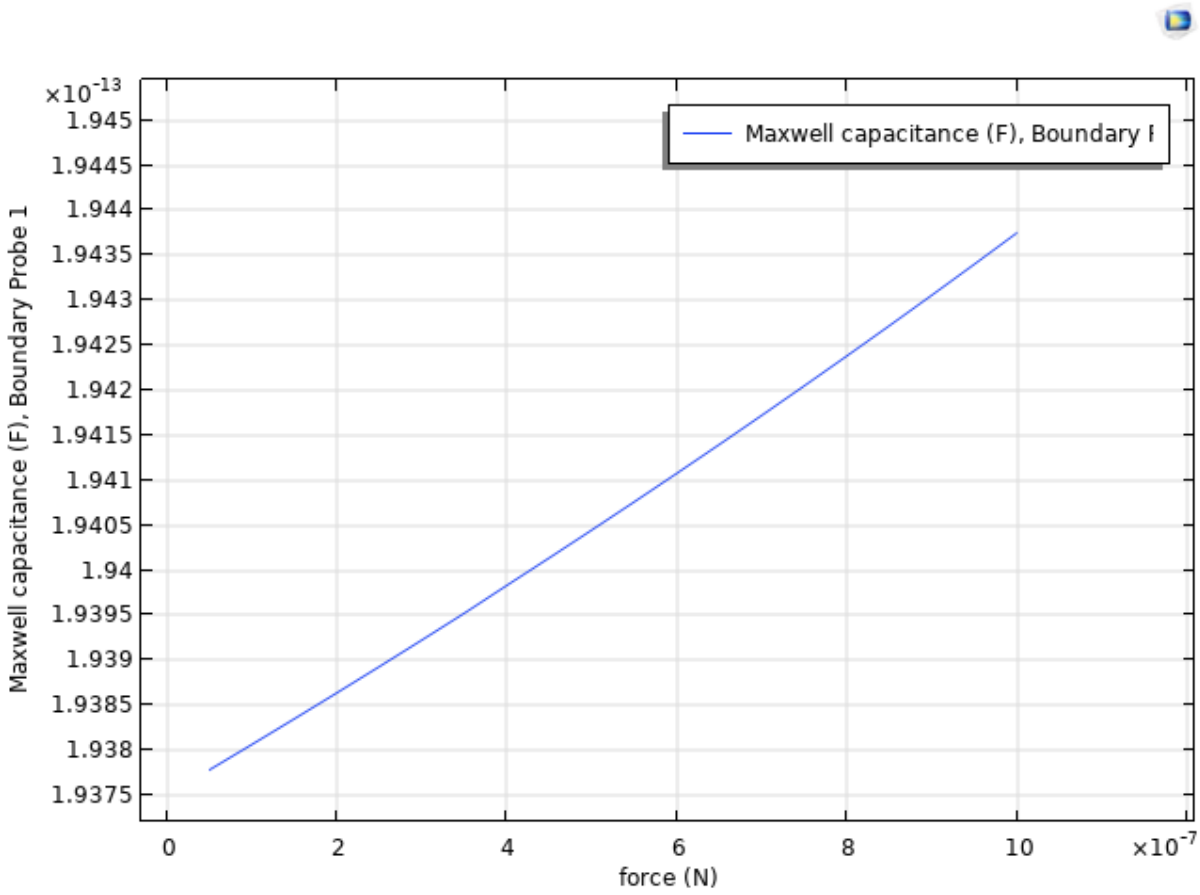
Sensing

The capacitance variation was simulated by conducting a parametric sweep of varying applied force on the gripper tip.

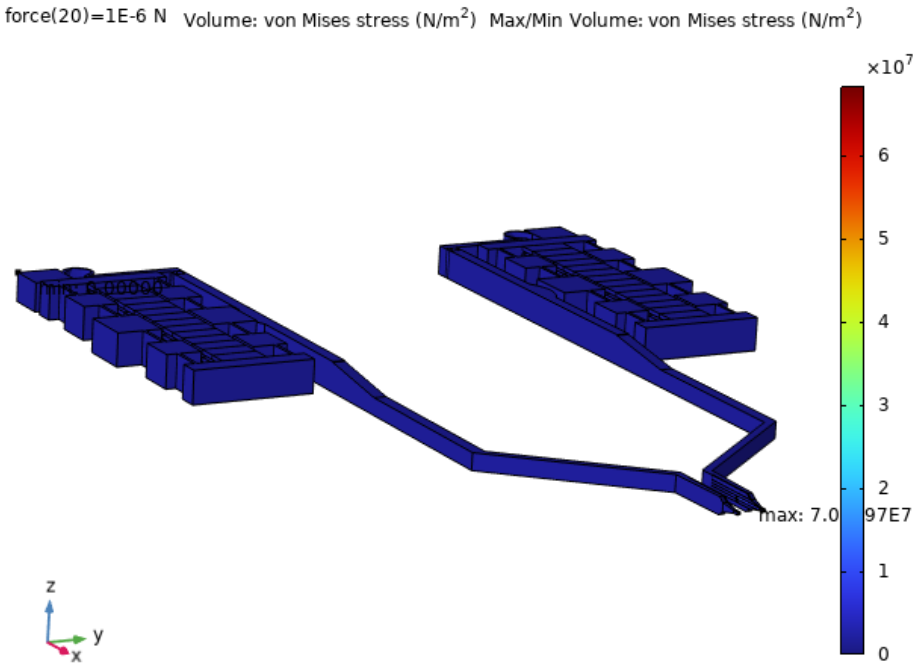
Given electric field (0 – 5V)



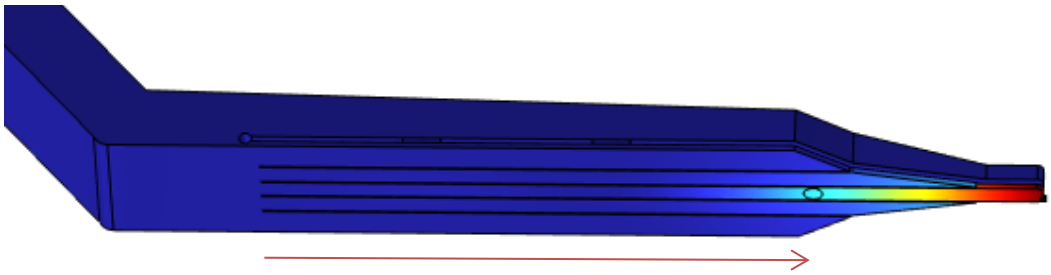
Capacitance varying over force applied



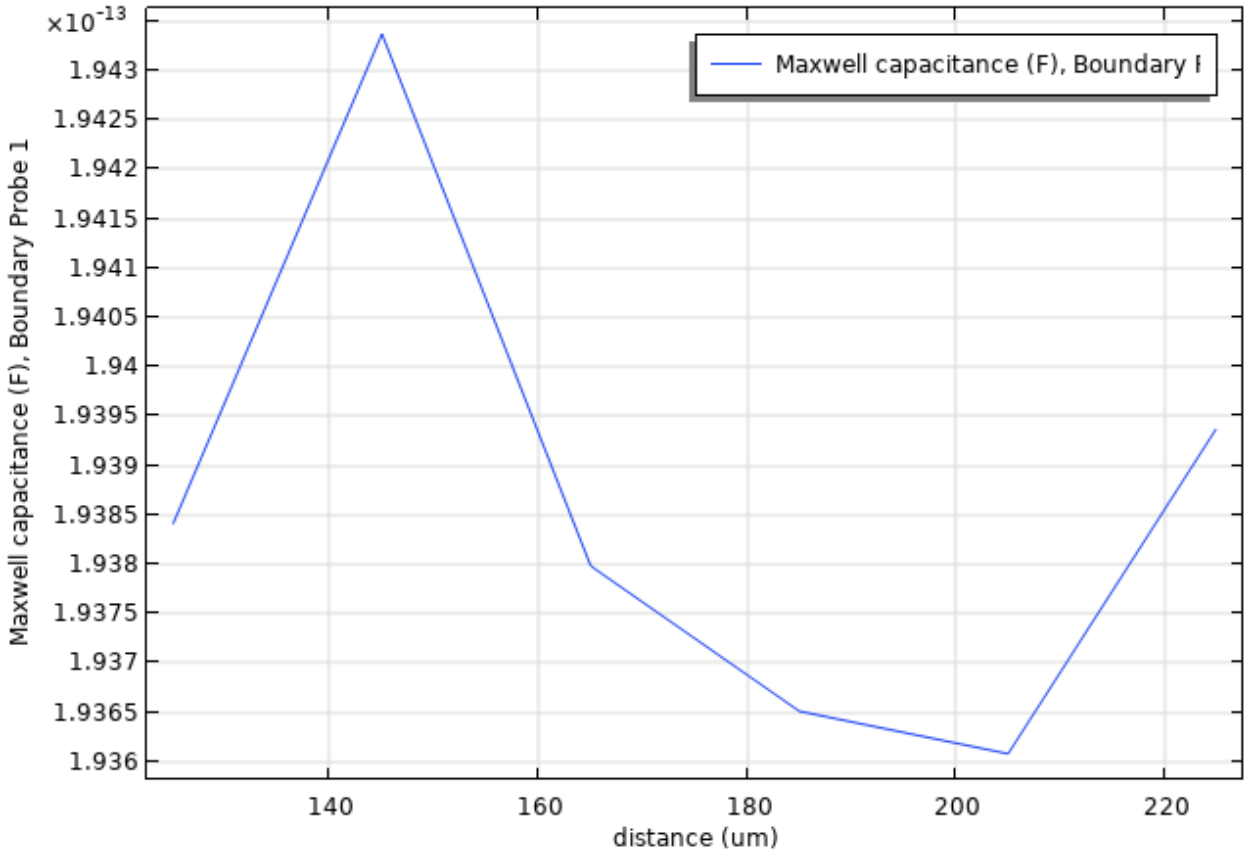
Stress variation for the maximum applicable force



Capacitance varying over force acting point



Force acting distance



8 FABRICATION PROCESS

The substrate will be a high-quality silicon wafer, 500 µm thick and 100 mm in diameter. The wafer will be selected based on excellent mechanical properties and a fine polished surface finish to enable the precise fabrication of the microgripper.

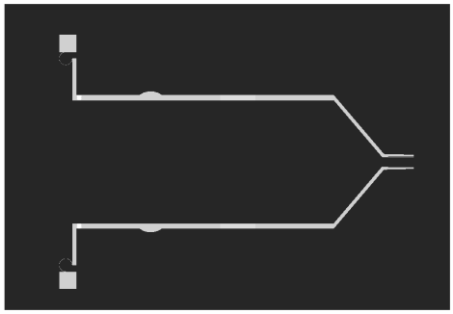
The selected wafer is then cleaned by the RCA cleaning process to remove organic contaminants, metallic residues, and particulates. This ensures a pristine and defect-free surface for subsequent deposition and patterning steps.

A 2 µm silicon nitride (Si_3N_4) layer is deposited over the silicon wafer using LPCVD. This layer provides the base for fixed anchor points and provides constraints for the moving parts of the microgripper, such as the jaw arms and bridge.

First, a layer of positive photoresist is spin-coated on top of the silicon nitride layer. Photolithography defining the mask 1 layout is performed with respect to the fixed constraints and connections of the moving parts of the gripper.

Exposed silicon nitride is etched 2 µm deep using RIE to create anchor points and connections for the moving parts. Photoresist remaining after lithography is stripped to finalize this layer.

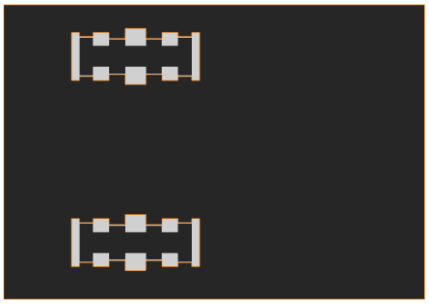
An 80 µm thick silicon nitride (Si_3N_4) layer is deposited by LPCVD. This layer provides the structural material for the jaw arms, which needs to have the mechanical strength and durability for precise operation.



A new layer of positive photoresist is spin-coated onto the silicon nitride surface. The geometry of the jaw arms, flexure hinges, and cantilever tip is defined by photolithography using mask 2 to achieve accurate feature formation.

The DRIE etches the silicon nitride layer to a depth of 80 µm, thereby forming the jaw arms and ensuring that the flexure hinges provide the smooth and precise movement as required.

A 100 µm thick silicon layer is deposited over the structure to form the bridge amplifier. This layer provides the structural stiffness necessary to amplify displacement efficiently.



A positive photoresist layer is spin-coated onto the silicon layer, followed by performing photolithography with mask 3 to define the geometry of the bridge amplifier. This will ensure the correct alignment and precision for the bridge layout.

The silicon layer is etched to a depth of 100 µm using DRIE to form the bridge amplifier. This step ensures uniformity and precision while maintaining the structural integrity of the amplifier.

The piezoelectric layer is deposited in five iterations by sputtering, with each layer being approximately 20 µm thick. After each deposition, annealing treatment is done to enhance the piezoelectric properties. Between the layers, dielectric filler material is used for mechanical stability and electrical isolation.

A thin metal layer, around 200 nm thick, is deposited by PVD to provide the electrodes needed for piezoelectric actuation and sensing. Photolithography and etching are used to define precise electrode patterns, ensuring electrical connectivity.

This will release the moving components comprising jaw arms, bridge amplifier, and cantilever tips from the substrate and keep the cantilevered tips floating and steady in the air.

The gripper tips are covered with Polydimethylsiloxane using spin coating or dipping, which will reduce stress to biological cells and enable their safe manipulation during operations.

The individual components are aligned and assembled so that precise connections are made between the jaw arms, bridge amplifier, and piezoelectric elements. The assembled gripper is tested for proper functionality and accuracy.

Packaging of the microgripper with biocompatible materials insulates it from environmental damages and makes safe operations in aqueous media possible. Packaging also enables the integration of the microgripper with any external system for completion.

9 CONCLUSION

It designs and develops a MEMS-based microgripper for biological cell manipulation, integrating advanced actuation and sensing technologies for cell handling, with diameters ranging from 10 to 100 microns with high precision. The microgripper will be actuated by the inverse piezoelectric effect, using PZT as the piezoelectric material to provide efficient and repeatable actuation. A silicon-based bridge amplifier with optimized flexure hinges amplifies the displacement, ensuring high precision in the operation of the microgripper. Real-time force feedback is provided by the capacitive sensing system, enabling the gripper to maintain applied forces within safe limits in the nanonewton to micronewton range, critical for handling delicate biological cells without causing damage.

Material selection played a crucial role in achieving the required performance. Si_3N_4 was selected due to its mechanical strength, wear resistance, and biocompatibility, making it suitable for the jaw arms and tip geometry. Additionally, the tips were coated with PDMS to further enhance biocompatibility and minimize stress on biological specimens. The fabrication process utilized advanced MEMS techniques, including LPCVD, DRIE, and PVD, to ensure precision in creating the complex features of the gripper. The structure was further coated and packaged with biocompatible materials to ensure safe operations in aqueous environments, integrating it with external systems.

Excellent precision, biocompatibility, and operational reliability establish the microgripper as a powerful tool for applications in cell biology, biotechnology, and medical diagnostics. Due to its modular and scalable design, it can be tailored for various biological applications, such as tissue engineering and manipulation of single cells. This project well-represents an effective combination of micro-scale engineering and biological research for advancement in bioMEMS technology, which opens new avenues in biomedical science.

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