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MORATUWA ENGINEERING RESEARCH CONFERENCE

DESIGN AND SIMULATION OF A MONOLITHIC MEMS PLATFORM FOR SINGLE-CELL INJECTION WITH INTEGRATED GRIPPING AND FORCE FEEDBACK

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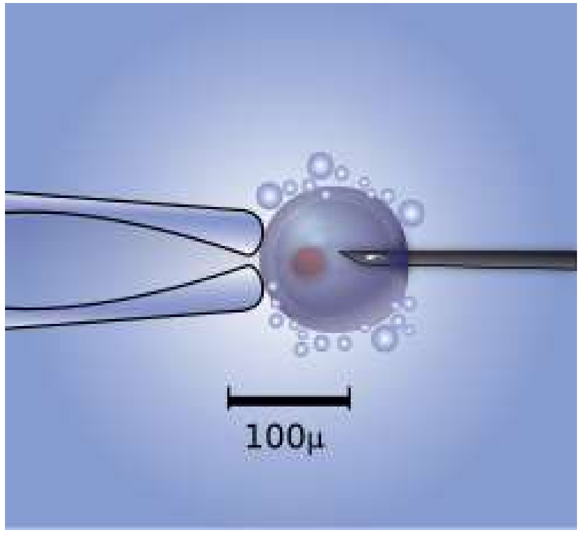
MOTIVATION: WHY CELL MANIPULATION & IMMOBILIZATION MATTER

- **Microinjection =** deliver agents **into a single cell** with a microneedle.
- **Why it matters:** core to **genetic engineering**, **drug testing**, **assisted reproductive technologies.**
- **What success needs:** only a **few µm** of **controlled tip travel**.
- **Why immobilize the cell:**

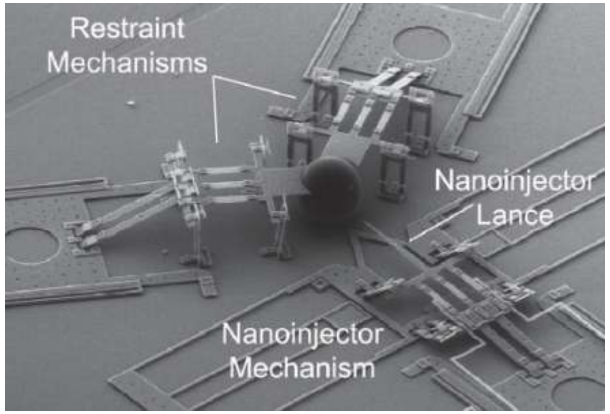
⇒ Prevents drift from fluid flow/vibration/stage motion

⇒ **Protects viability** (lower shear/compression, fewer membrane tears)

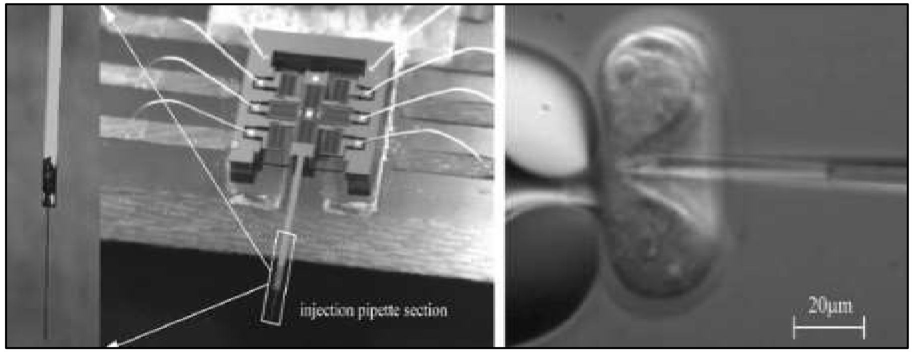
⇒ Improves **repeatability & throughput,** supports batch work



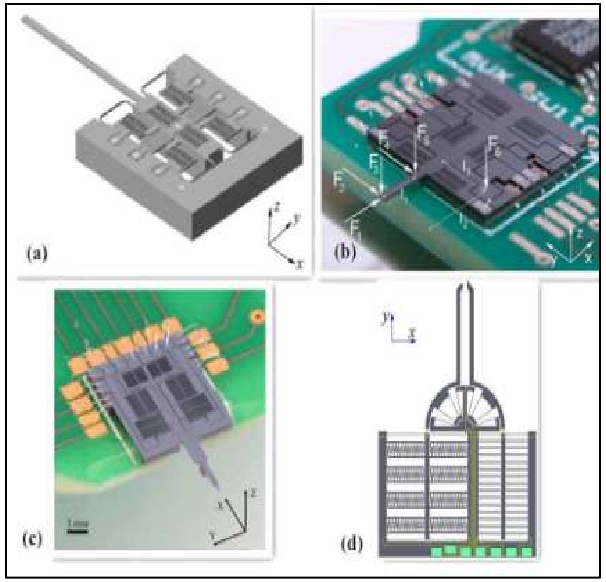
CURRENT LANDSCAPE OF MICROINJECTION SYSTEMS



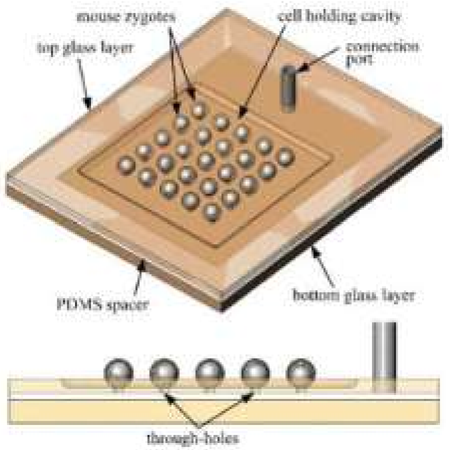
A surface-micromachined cell injector



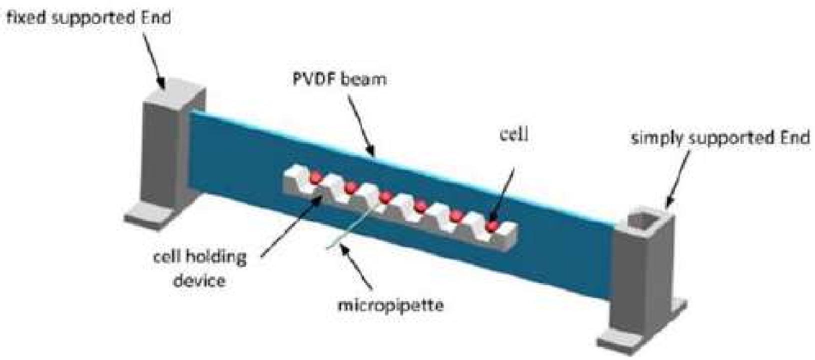
Wire-bonded force sensor with an attached injection pipette



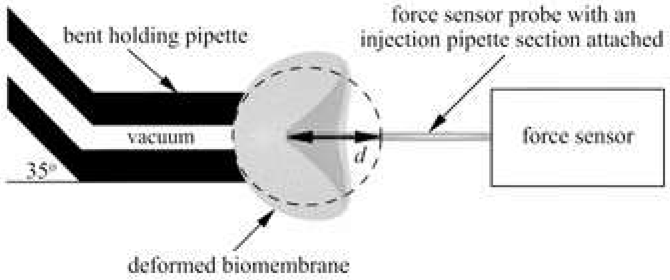
Piezoelectric and capacitive microforce sensors



Vacuum-based cell holding device



Groove - based cell holding device



Vacuum-based cell holding device

RESEARCH GAP

Operator-dependent, bulky, no force feedback

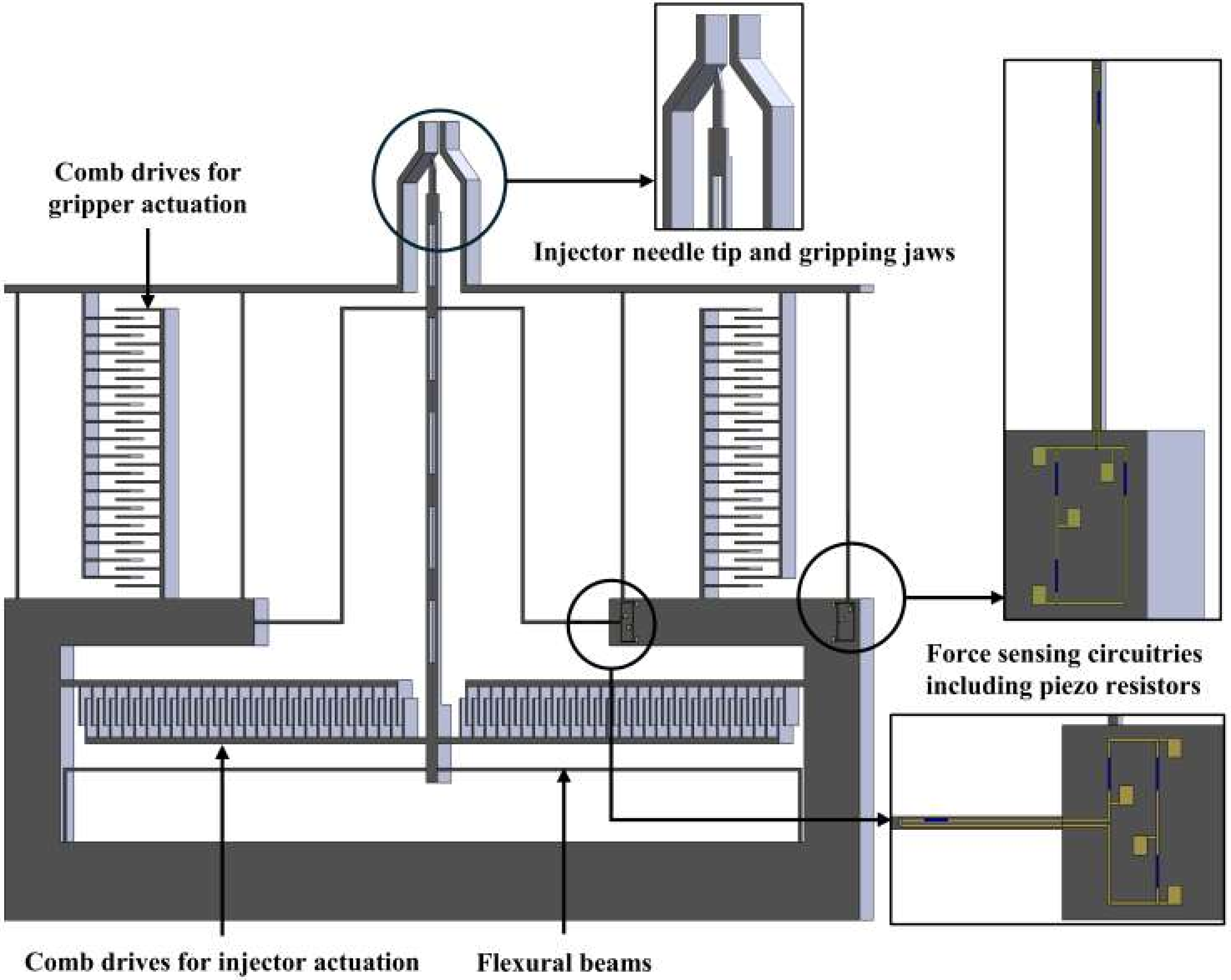
→ cell-damage risk, low precision & throughput.

High precision & small footprint yet **gripping and injection are separate,** and **sensors are external**

→ **indirect measurements**, **alignment issues**, **complexity**.

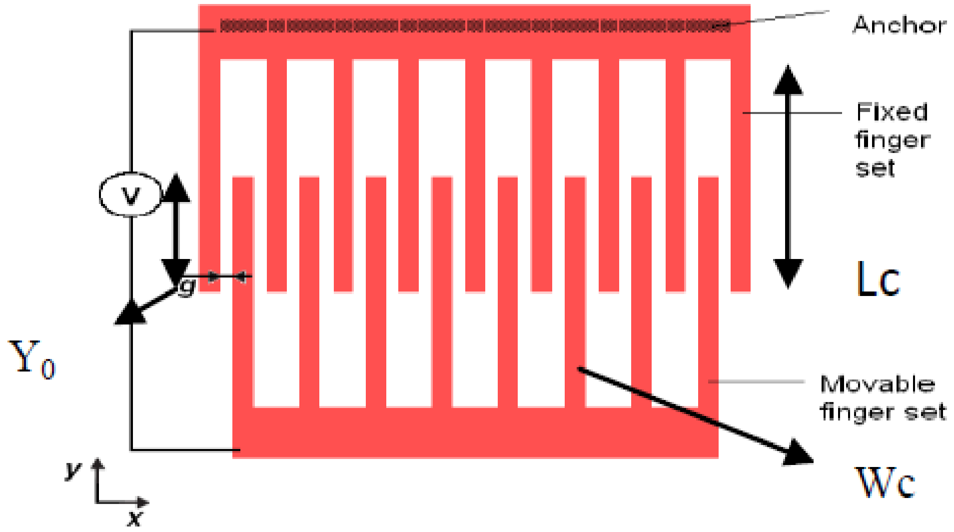
Gap we address:
A **single, monolithic MEMS platform** that **integrates gripping, injection and in-situ piezoresistive force sensing** for **safe, automated, high-throughput** single-cell injection.

PROPOSED SYSTEM



WORKING PRINCIPLES - ACTUATION

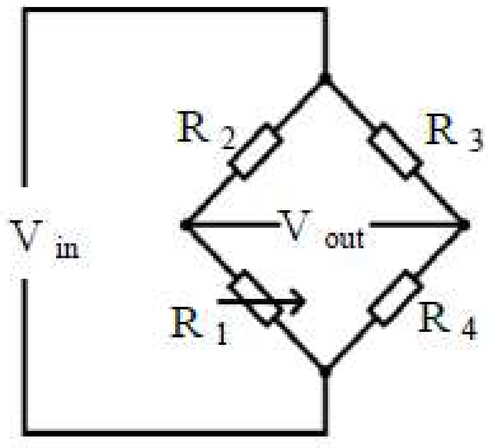
- **Effect:** Voltage across interdigitated sidewalls produces an attractive force, pulling the shuttle **in-plane** to increase finger overlap.
- **Implications:** Linear, pull-in–free translation, smooth µm-scale motion, displacement set by suspension stiffness.
- **Why this method:** Chosen for its **fast, low-power, and highly precise in-plane motion**, ideal for micrometer-scale injection and gripping in MEMS.



Lateral movement configuration of comb drives

WORKING PRINCIPLES - SENSING

- **Effect:** Mechanical stress on doped silicon changes its resistivity via the piezoresistive effect.
- A quarter-bridge Wheatstone circuit converts small ΔR into a proportional voltage.
- **Why it works well here:** High sensitivity, temperature compensation, and noise suppression due to its differential measurement approach → enables **real-time, reliable force feedback** for injector and gripper without bulky sensors.



Quater bridge Wheatstone setup

DESIGN TARGETS & CONSTRAINTS

Target Cell Size: 10–20 μm

→ Design range 8–20 μm.

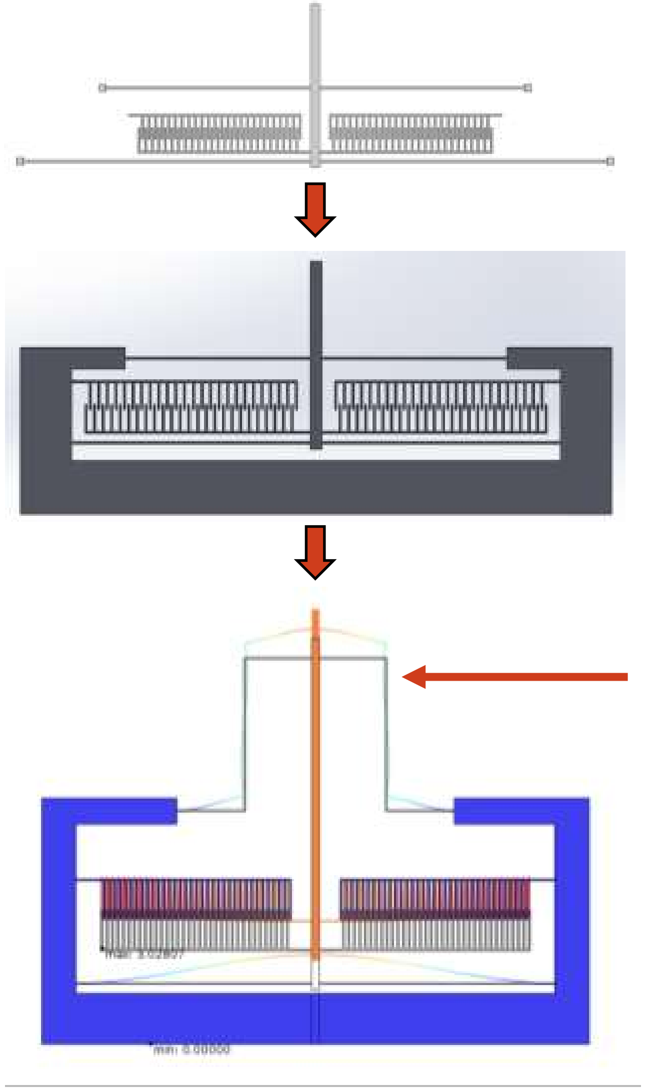
Injector Stroke: ≥ 5 μm tip displacement

Injecting Method: biocompatible substrate coated on the needle

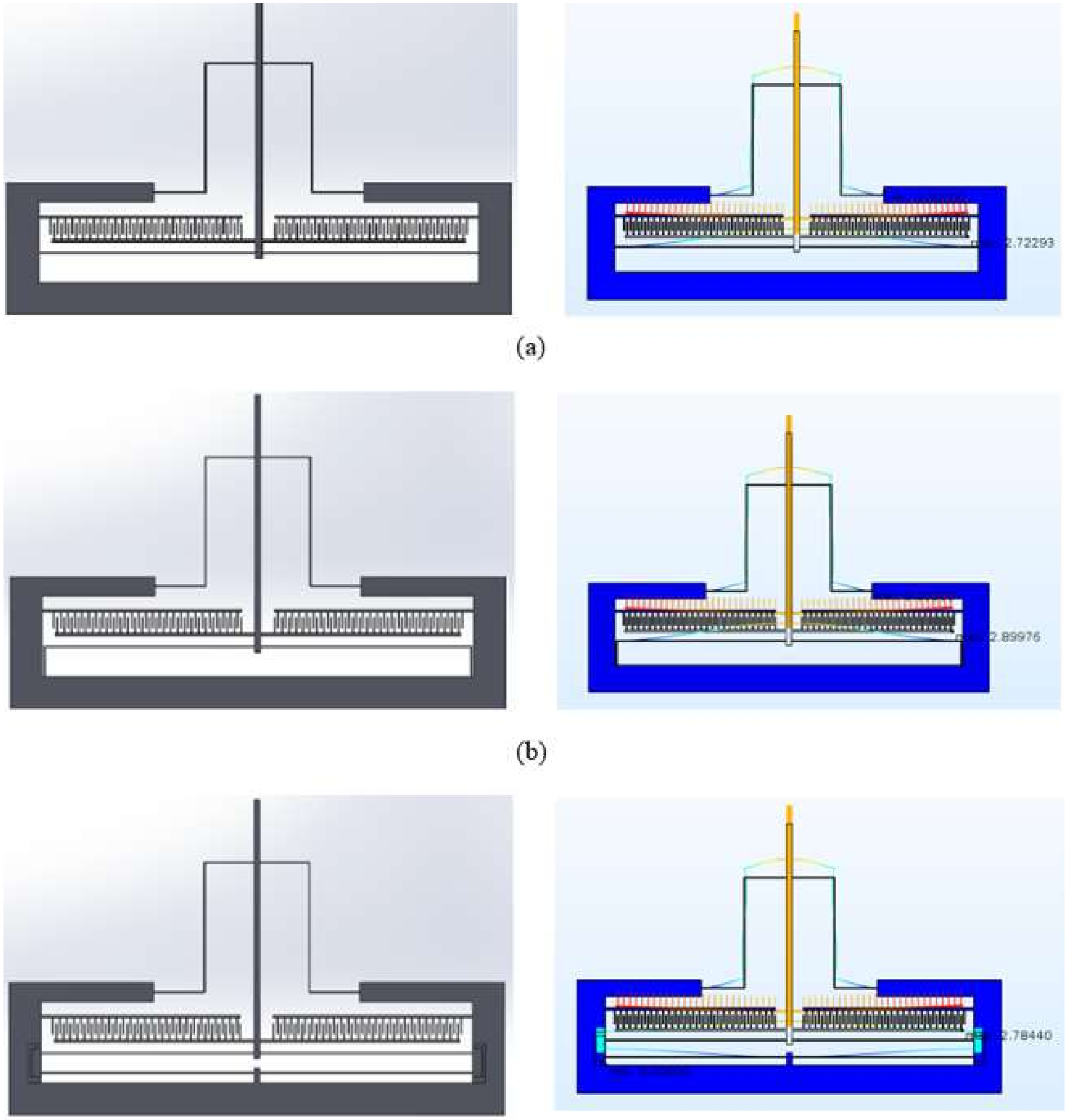
Sensor Sensitivity: ≥ 5 mV , low noise.

Safety Limits: Max contact force → injector < 20 μN, gripper < 50 μN.

DESIGN - INJECTOR



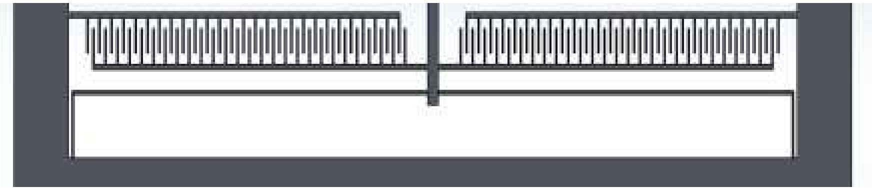
The modified flexural beam design increased the injector tip displacement to 2.5 μm, also addressing needle tip misalignment during actuation, thereby enhancing overall precision.

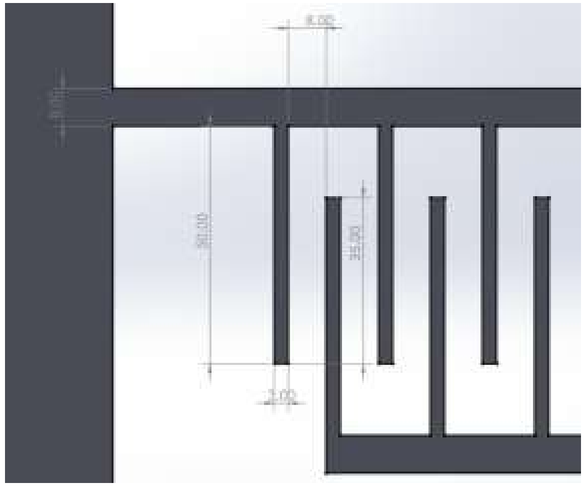


At 120V, the maximum displacement was achieved using the **crab-leg** flexural beam structure, making it the preferred choice for further design development.

DESIGN - INJECTOR

Optimized comb driver set for maximum displacement and dimensions





Number of Teeth on the fixed comb = 27× 2

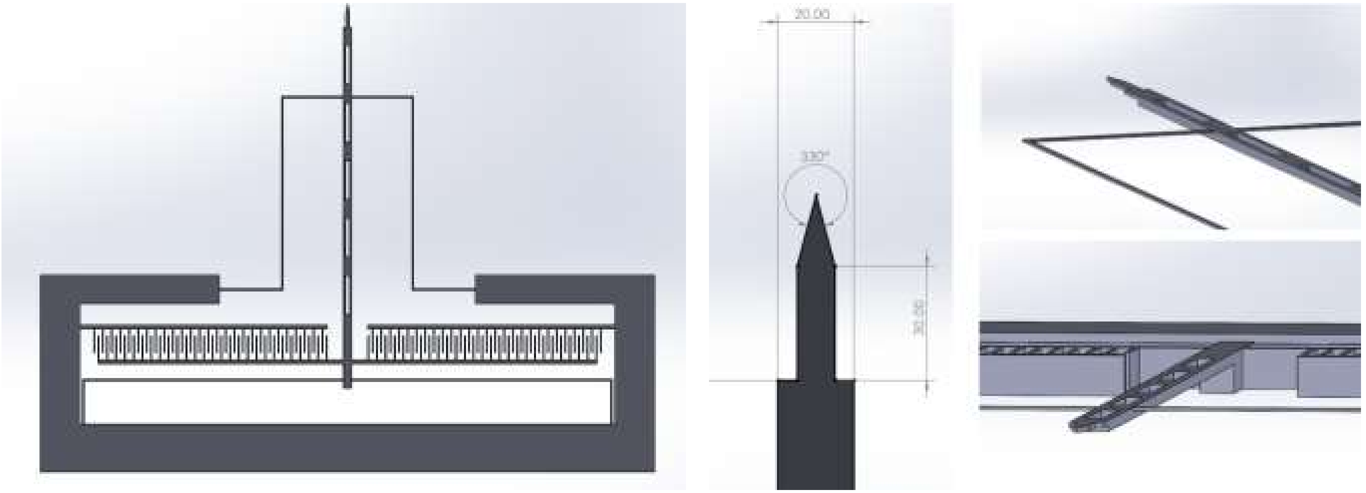
Number of Teeth on the moving comb = 27× 2

Thickness of the comb fingers = 25 μm

Flexural beam width = 4 μm

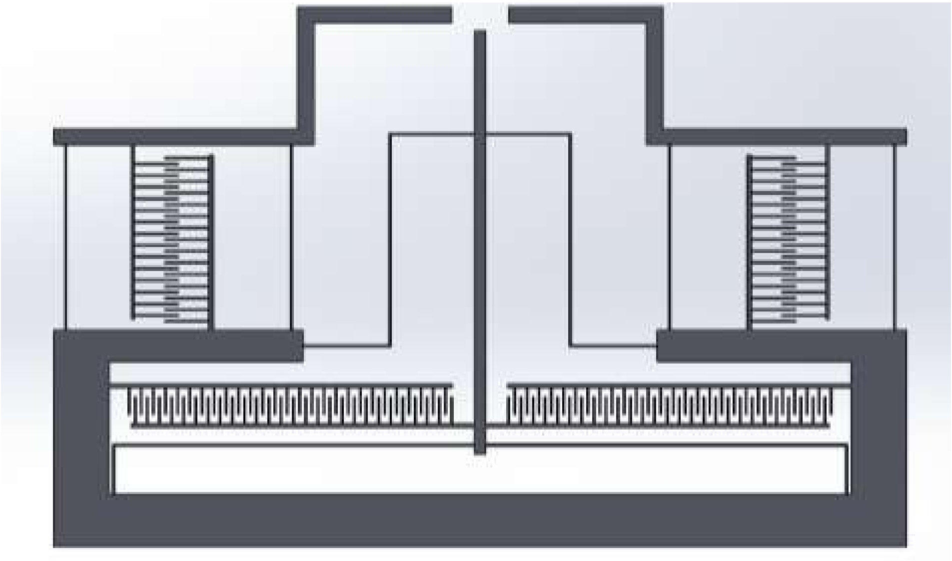
Flexural beam Thickness = 2 μm

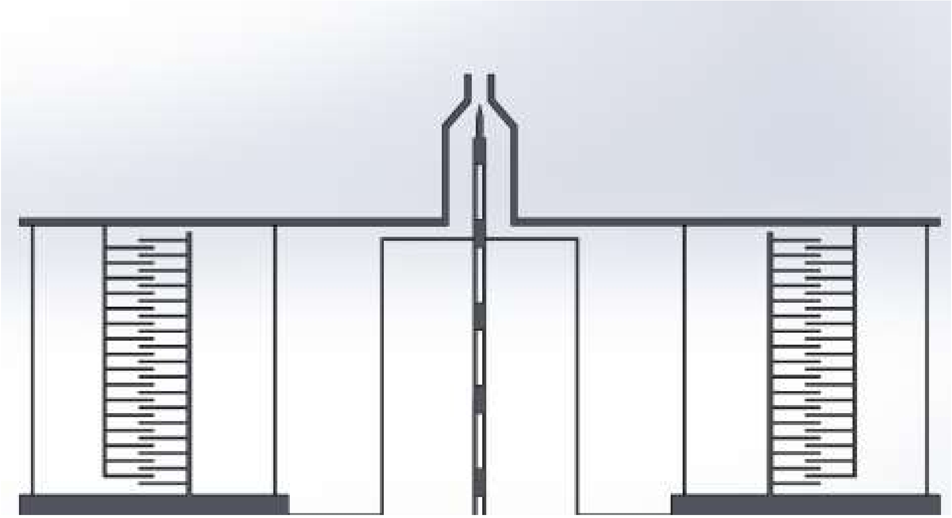
Maximum displacement = 6.825 μm at 150V

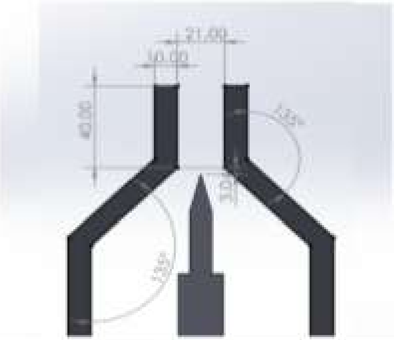


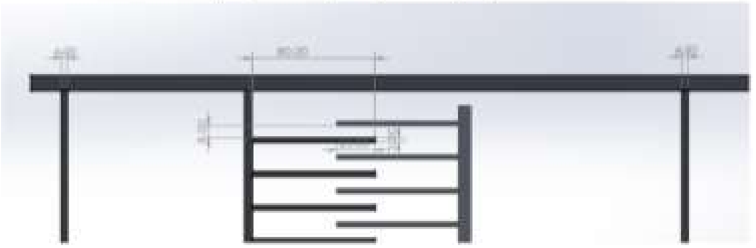
Modifications to the needle section, including weight reduction, buckling prevention, enhanced sharpness, and slot incorporation, improved performance by increasing eigenfrequency and system stability.

DESIGN – GRIPPER INCLUSION



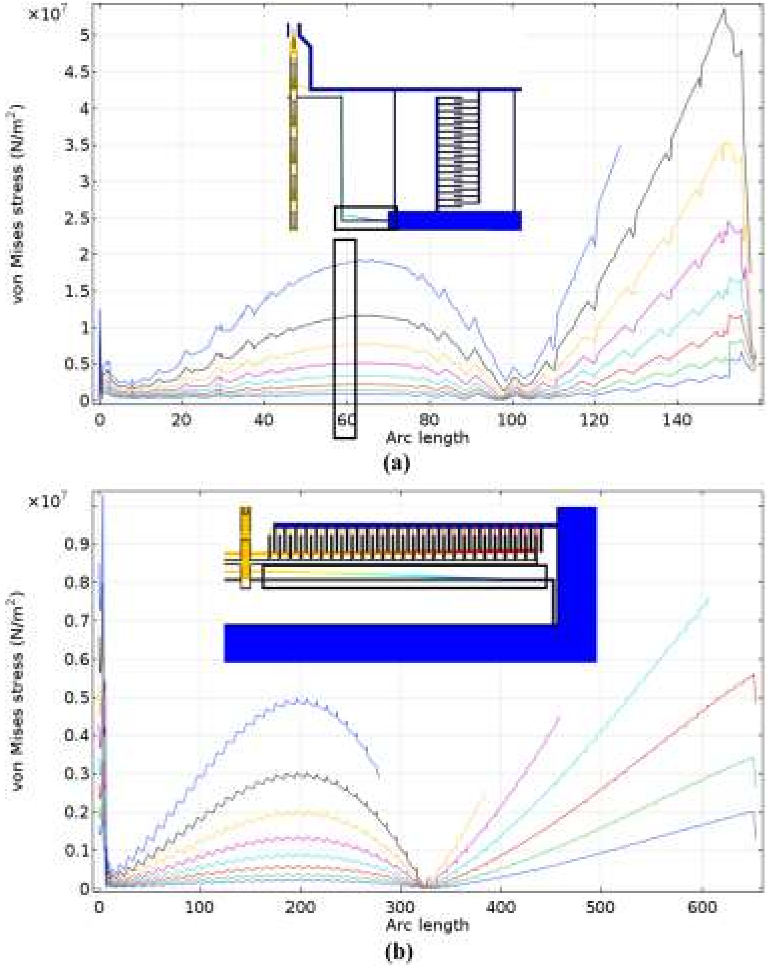


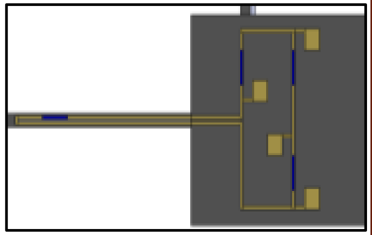


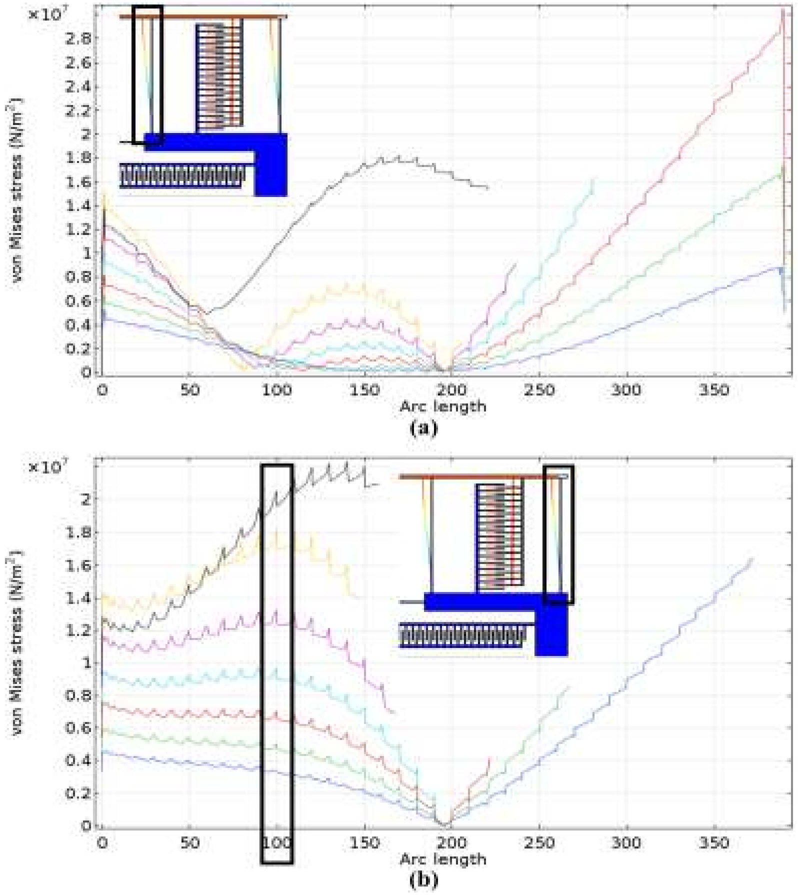


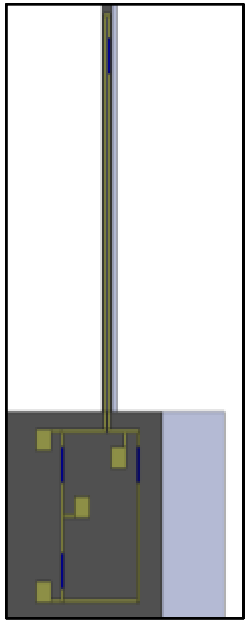
The dual-arm configuration ensures stable, precise cell handling without damage, allowing fine positioning for injection and versatility to accommodate varying cell sizes

DESIGN OF THE FEEDBACK SYSTEM (SENSORS)





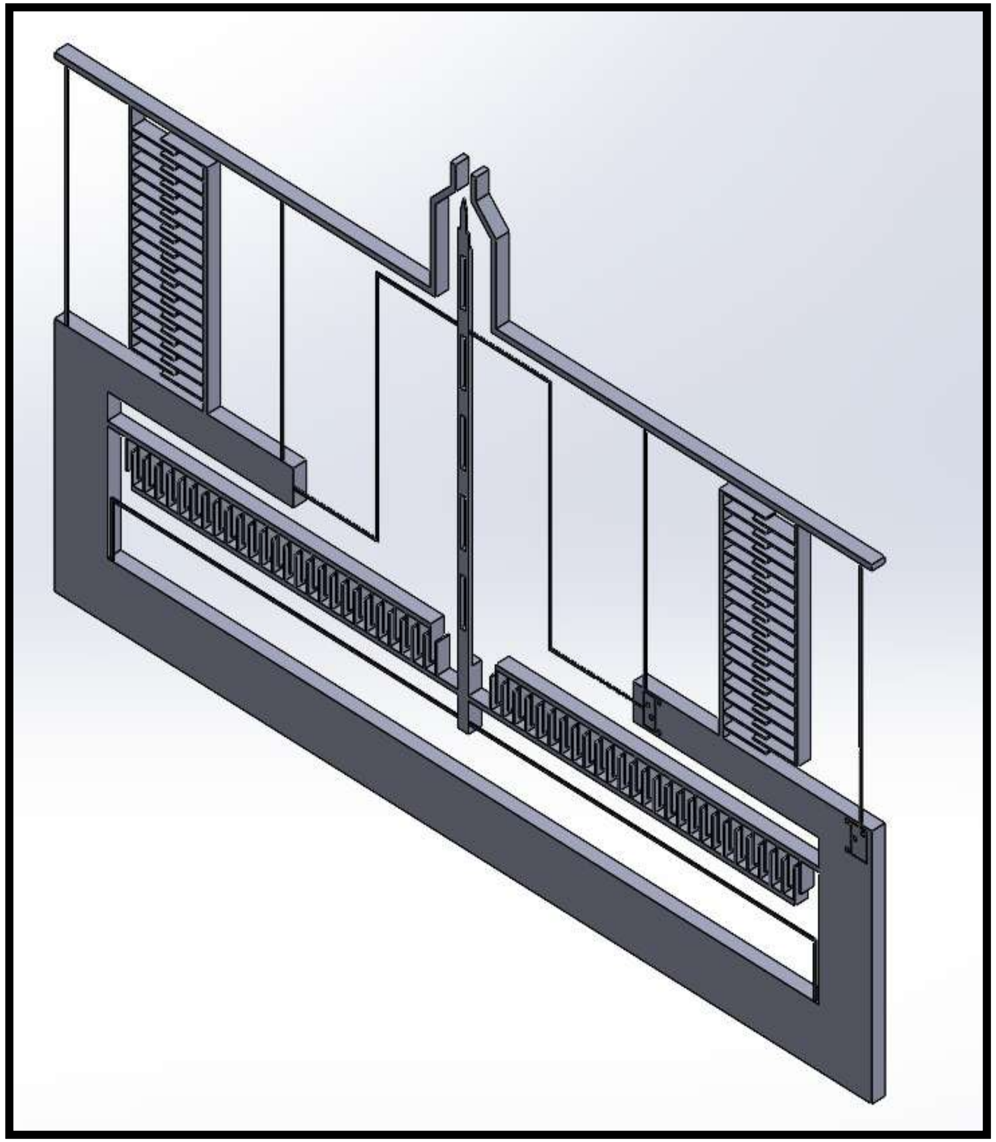


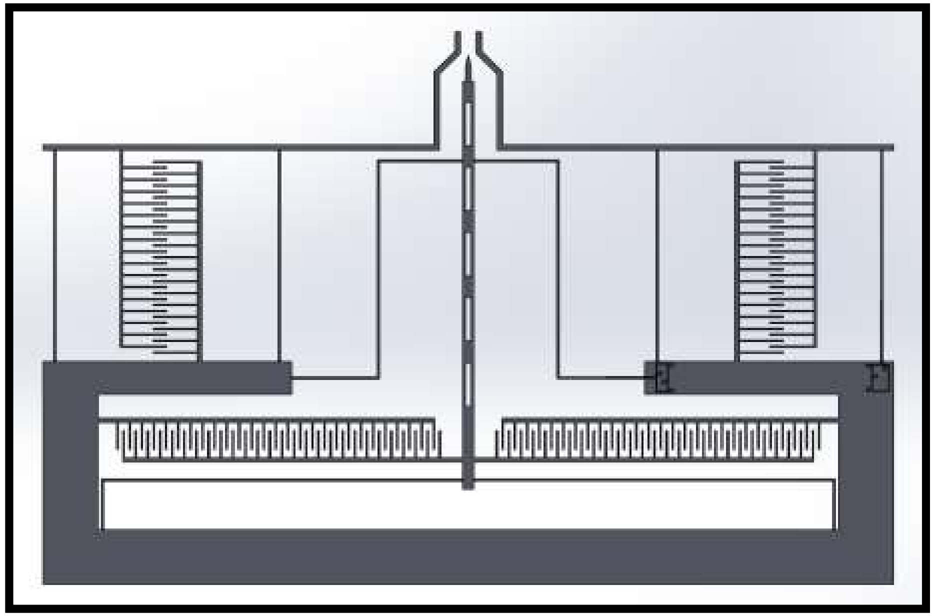


Piezoresistive material was strategically deployed based on stress analysis. The circuit design includes voltage supply pads and sensing pads.

A quarter-bridge Wheatstone circuit was chosen for the force sensing of the injector and gripper units due to the thin suspension beams, which limited the feasibility of a half-bridge configuration.

FINAL DESIGN & MATERIALS





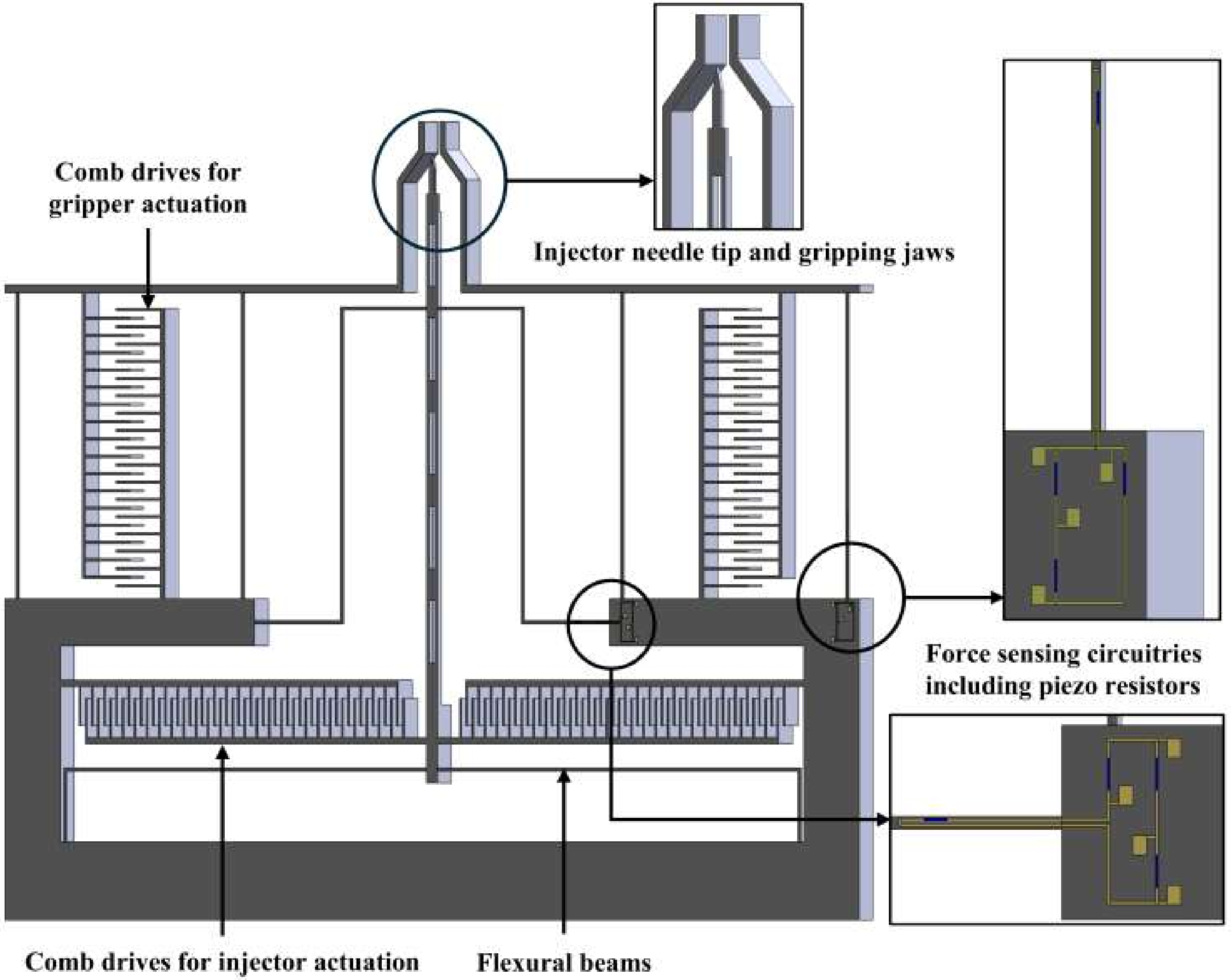
→ Structural Material: **Single-crystal (Anisotropic)** silicon for precision and strength

→ Dielectric Material: **Air** for simplicity, cost-effectiveness

→ Piezoresistive Material: **P-type doped silicon** for high sensitivity and precision in force sensing.

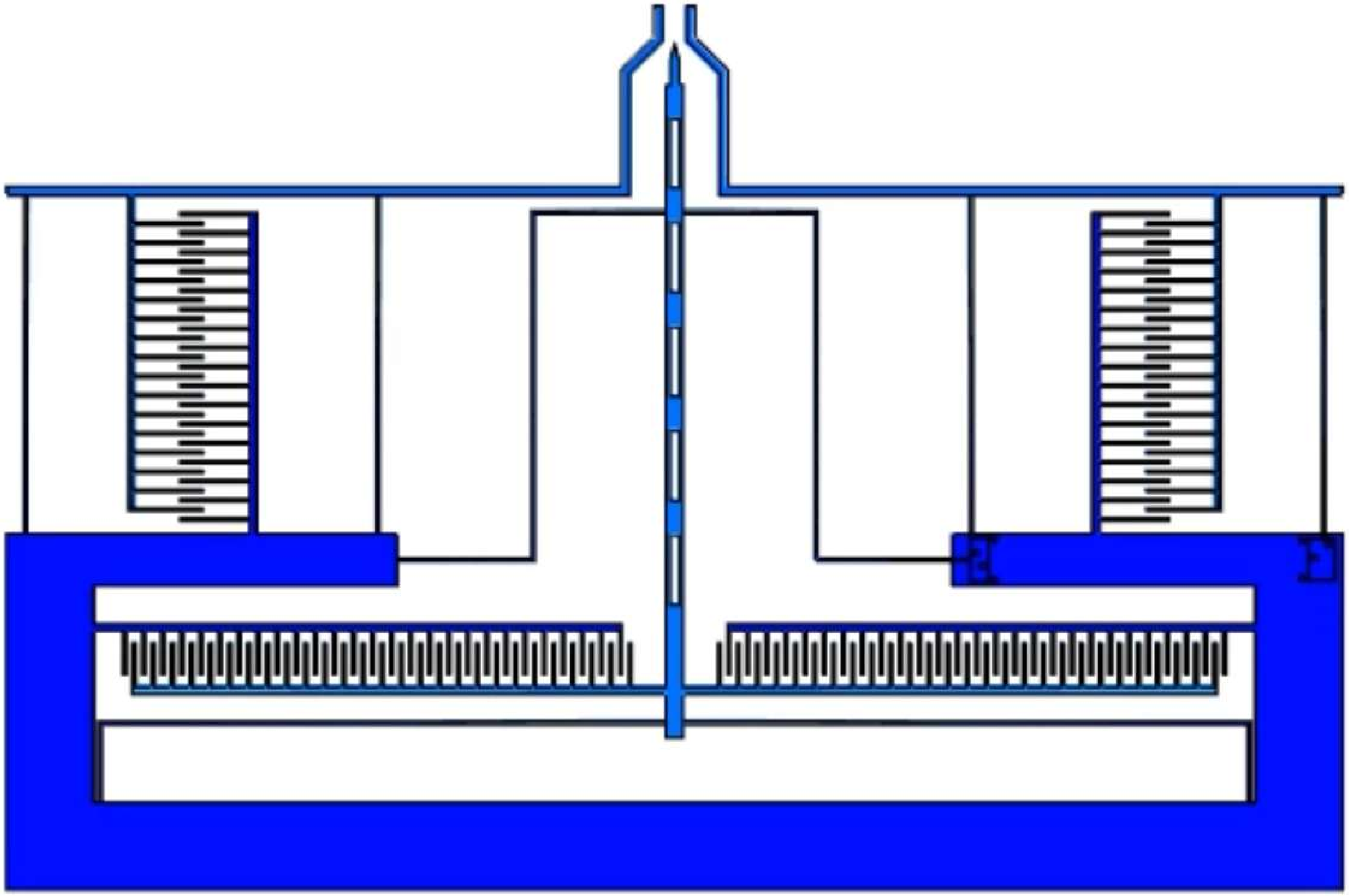
→ Conductor Material: **Gold** for superior conductivity, corrosion resistance, and biocompatibility.

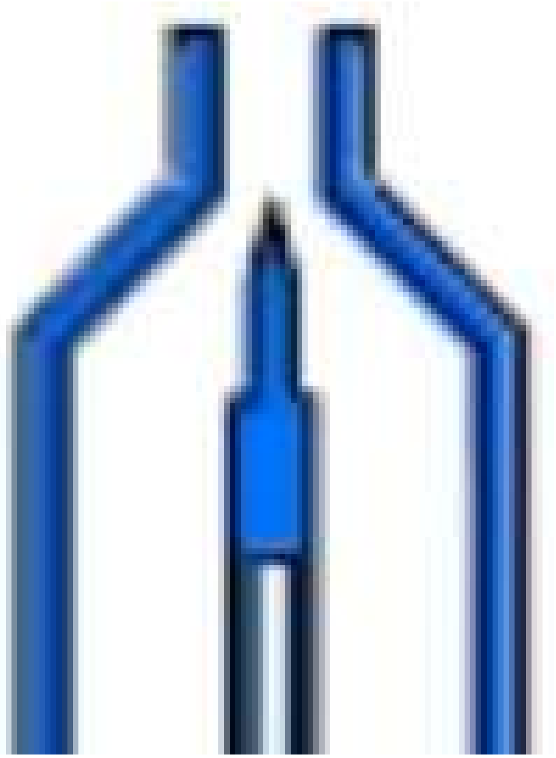
STRUCTURAL DESIGN & KEY FEATURES



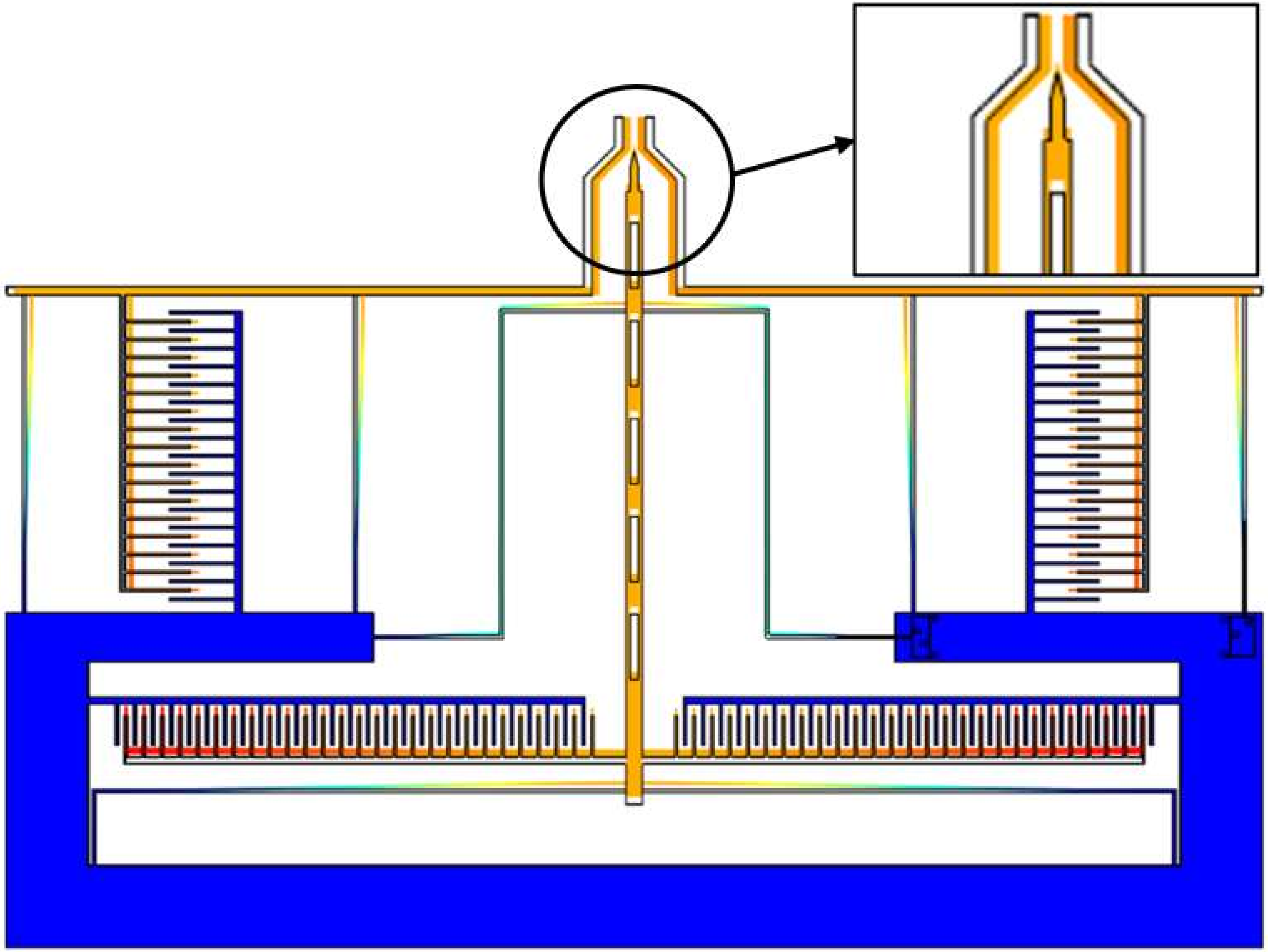
Parameter	Value
Total length	1018 μm
Total width	1540 μm
Total thickness	25 μm
Injector width	20 μm
Gripping arm width	10 μm
Gripping arms initial opening	21 μm
Finger pair number of injector	54
Finger number of each gripping arm	14
Injector comb fingers length	50 μm
Gripper comb finger length	80 μm
Width of all comb fingers	3 μm
Initial overlap length of injector comb fingers	35 μm
Initial overlap length of gripper comb fingers	25 μm
Gap between comb fingers	8 μm
Width of flexible beams	4 μm
Thickness of flexible beams	2 μm

SIMULATION

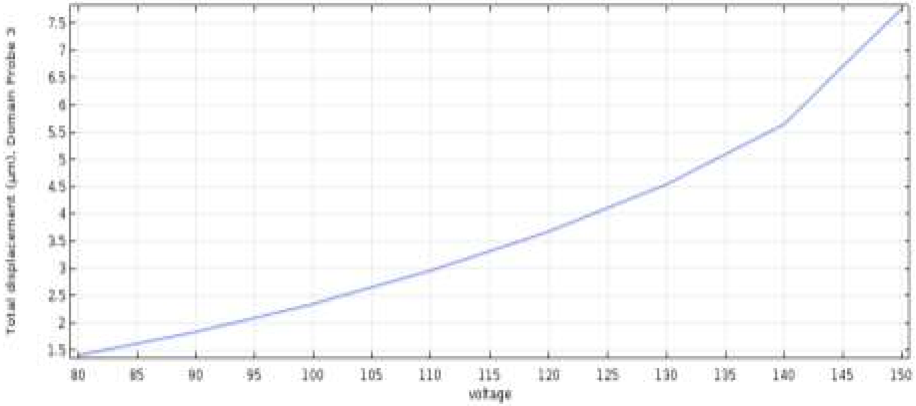


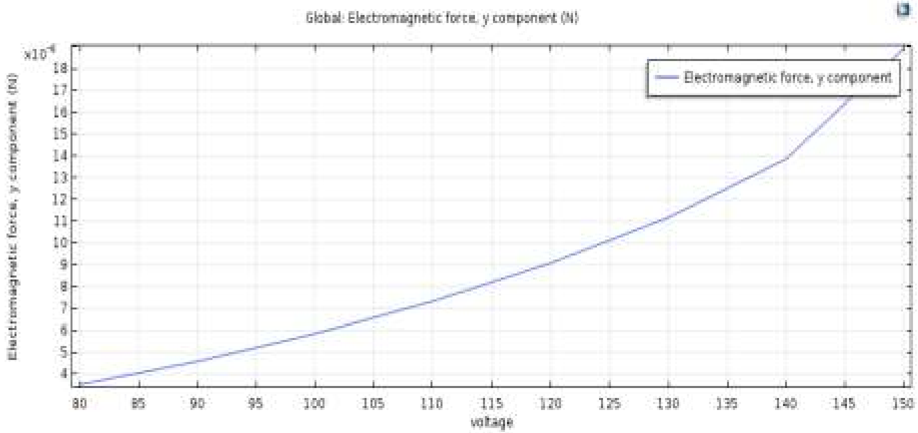


SIMULATION

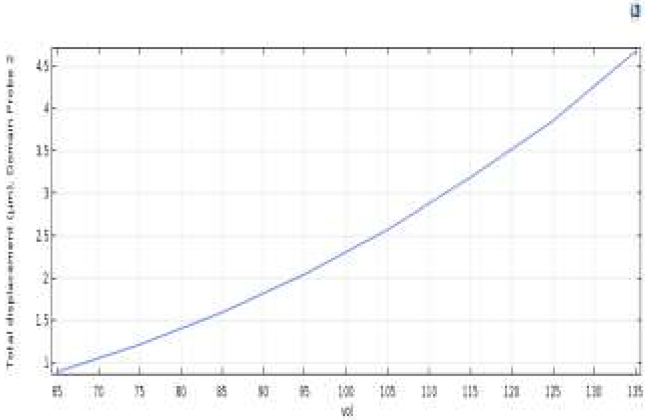


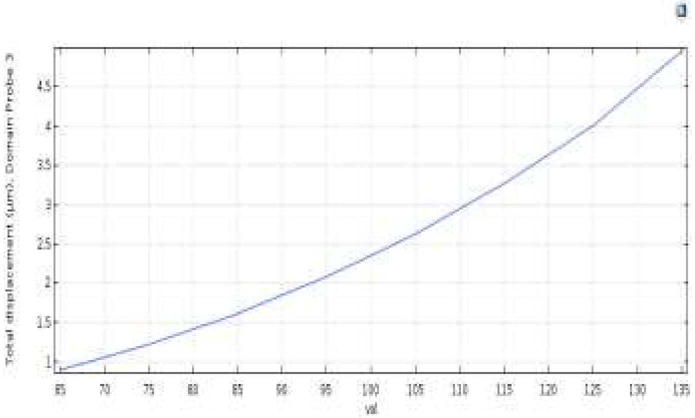
SIMULATIONS & RESULTS – ACTUATIONS

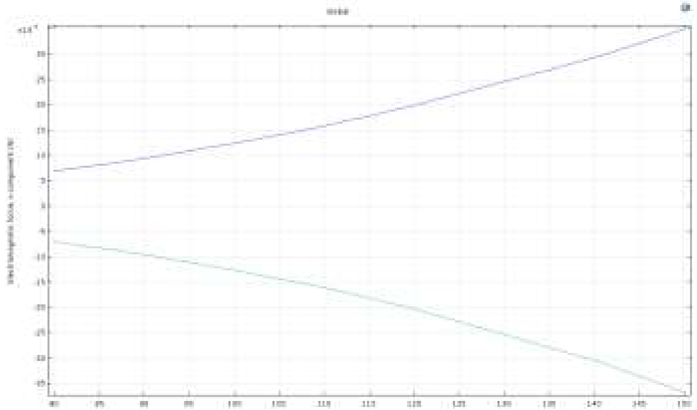




The injector achieves over 5 µm displacement and generates sufficient force (10–20 µN) for precise cell injection, effectively penetrating membranes without damage.

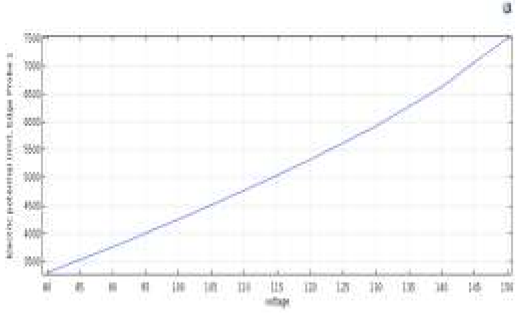


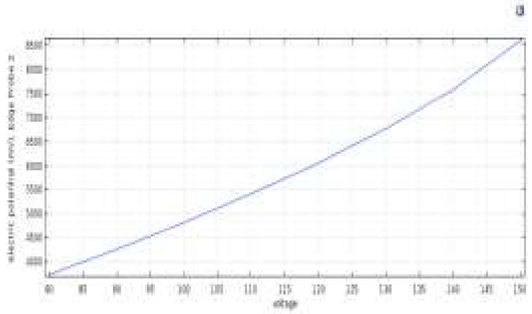


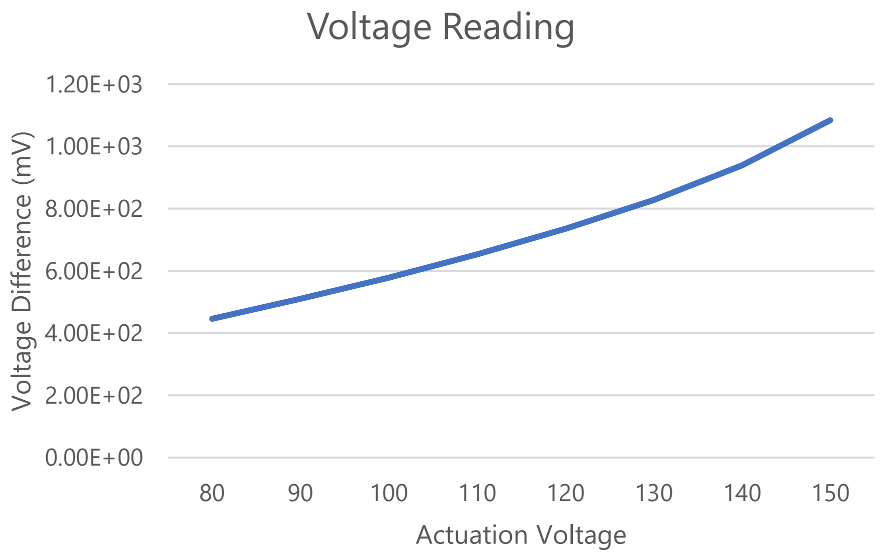


The gripper ensures stable operation by applying controlled force to securely hold 10–20 µm cells without slippage or damage.

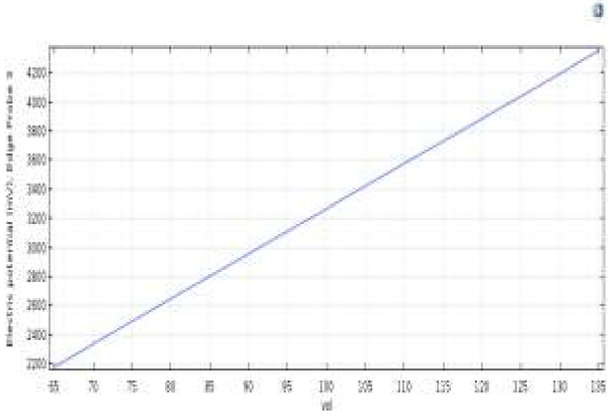
SIMULATIONS & RESULTS – SENSORS

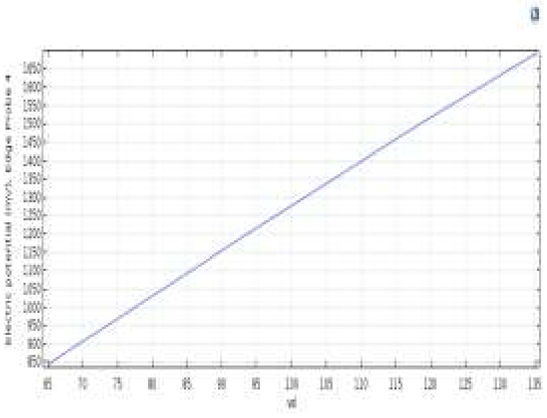


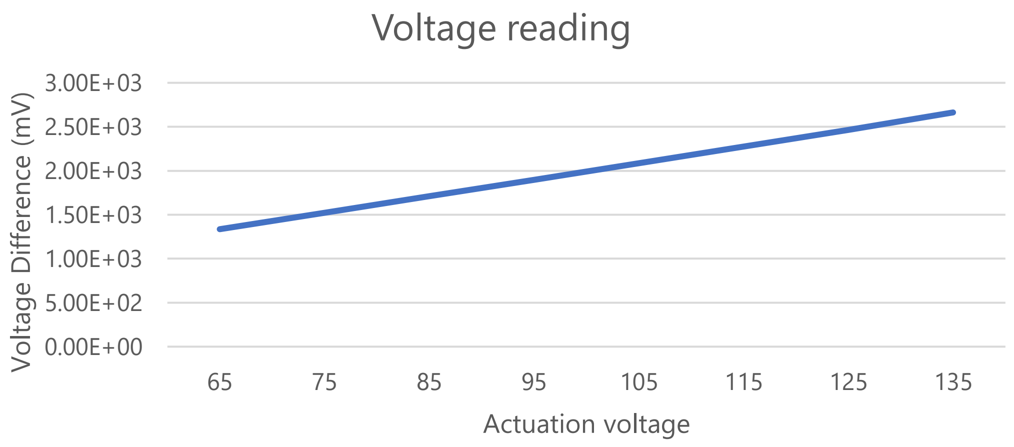




Injector sensor sensitivity = 9.43 mV



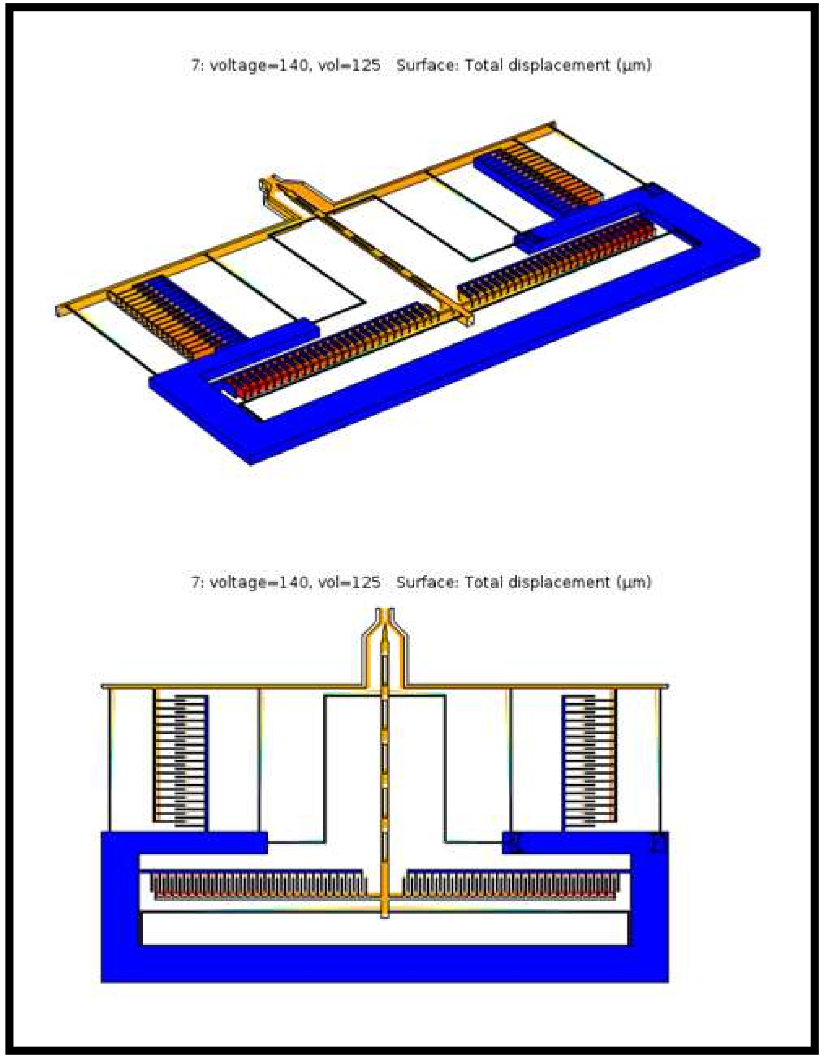




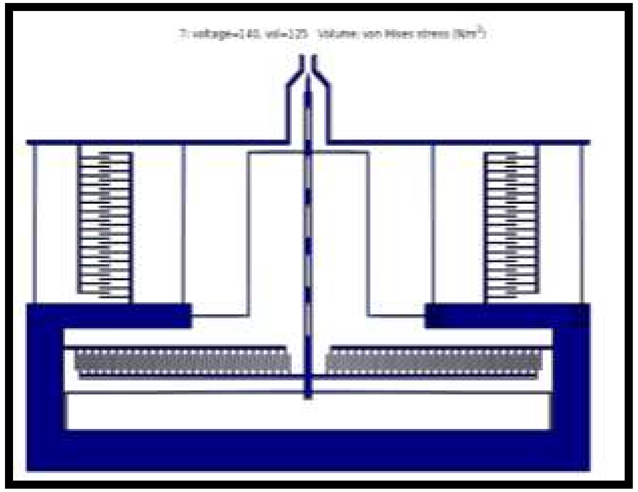
Gripper sensor sensitivity = 19 mV

SIMULATIONS & RESULTS – PLOTS

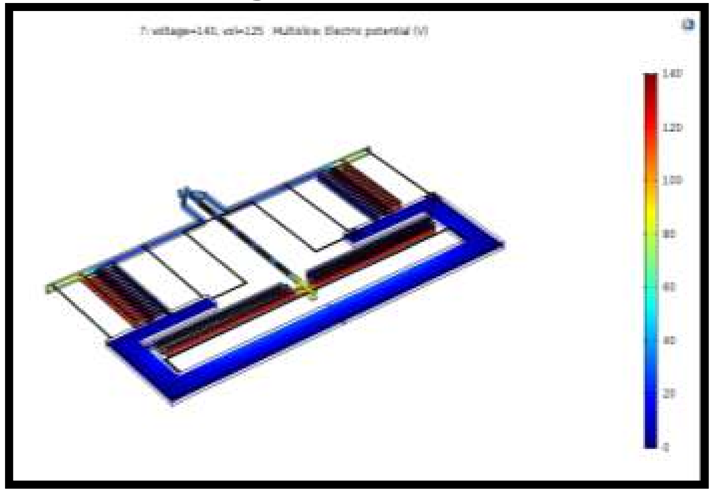
Displacement Field



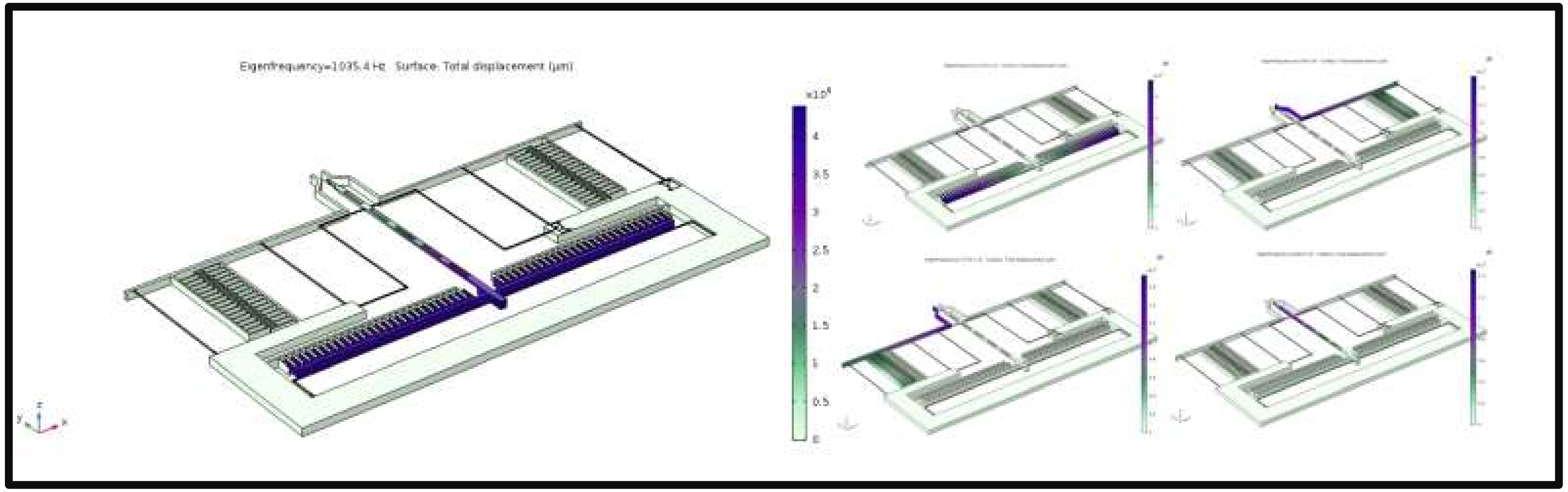
Stress Distribution



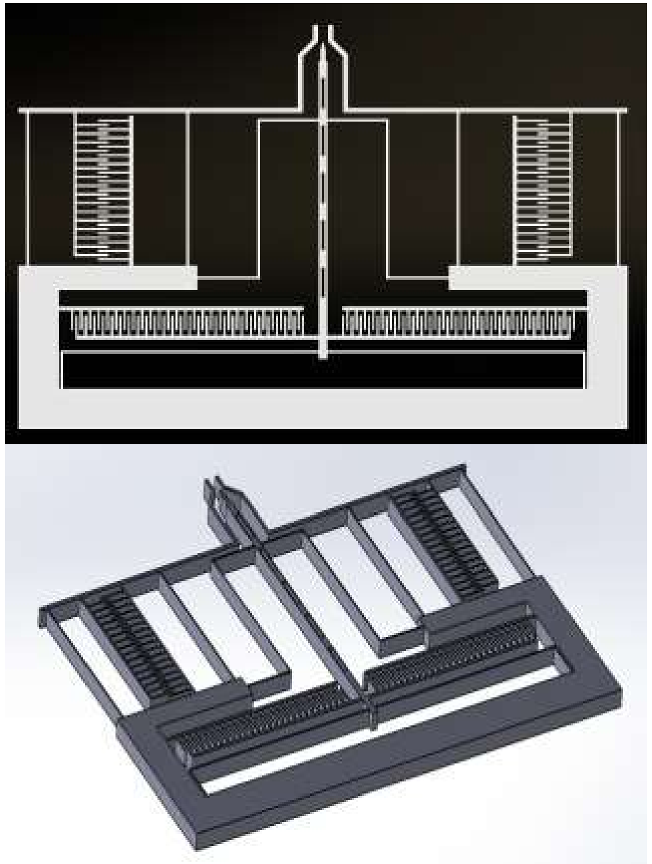
Voltage Distribution



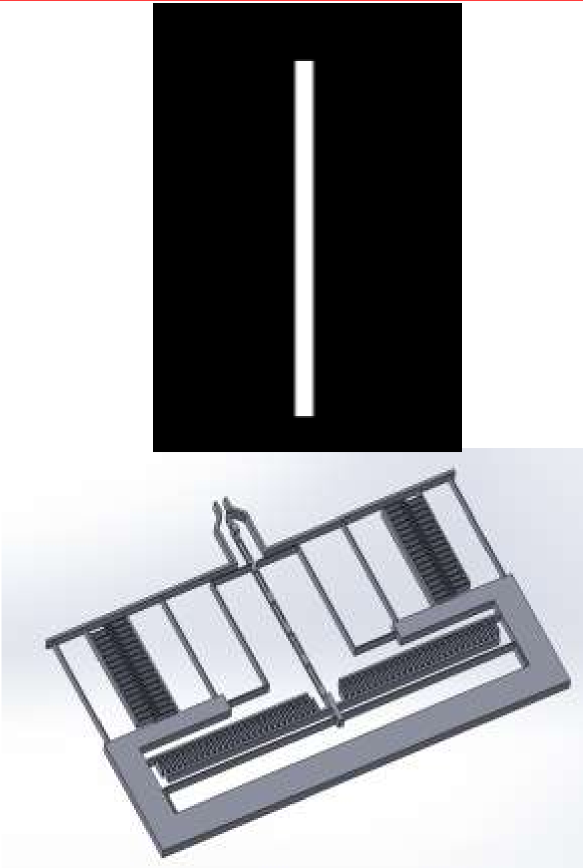
Modal Analysis



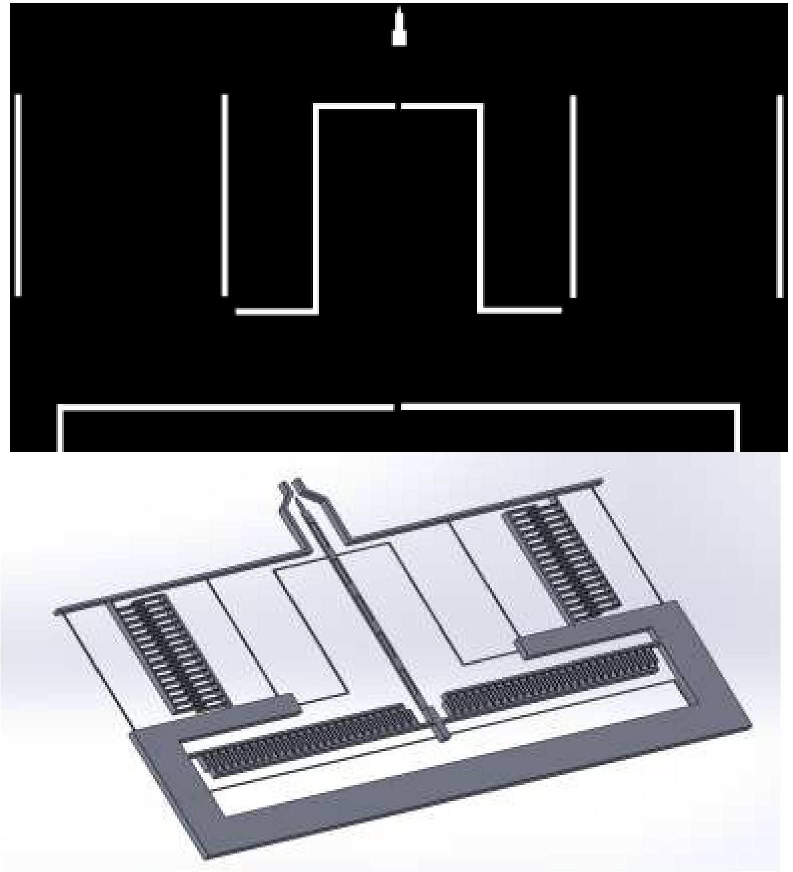
FABRICATION



→ Positive PR
→ DRIE for front side
→ No etch stopping

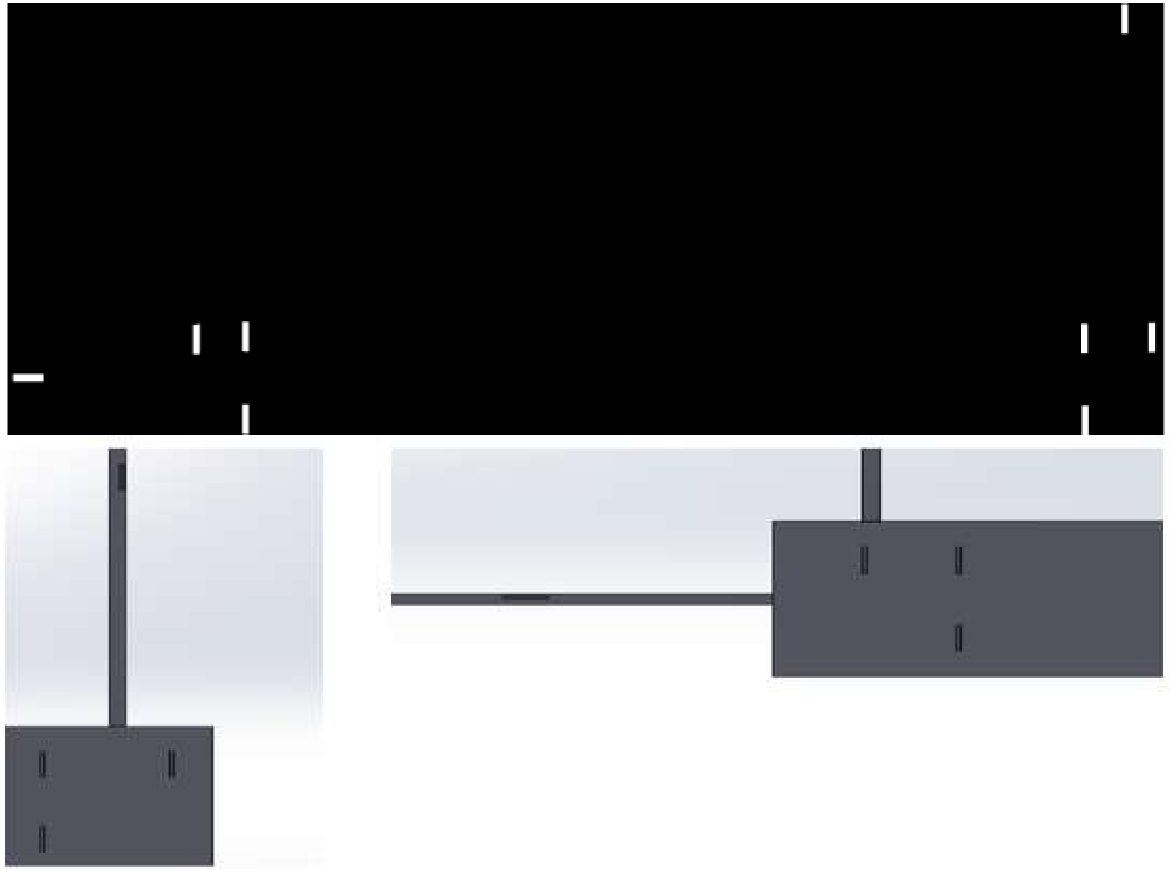


→ Positive PR
→ DRIE for back side
→ Etch stopping at 18 microns

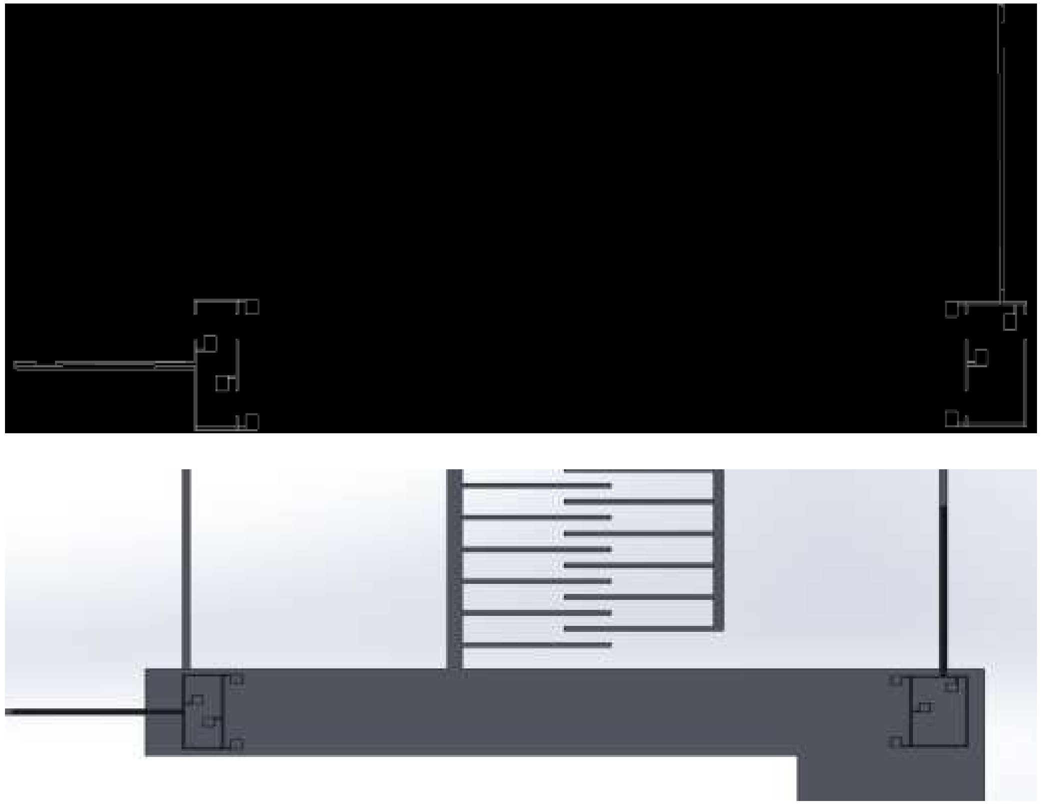


→ Positive PR
→ DRIE for back side
→ Etch stopping at 23 microns

FABRICATION



The liftoff process uses positive photoresist to define regions for material deposition, followed by PVD or CVD to deposit p-doped silicon. Acetone removes the photoresist, lifting unwanted material and leaving precise patterns.



Do the similar process to deposit gold.

CONCLUSION & FUTURE PROSPECTS

CONCLUSION

- Developed a **monolithic MEMS platform** integrating:
  - ⇒ Lateral comb-drive injector
  - ⇒ Dual-arm microgripper
  - ⇒ In-situ piezoresistive force sensing
- **Simulation results:**
  - ⇒ Stroke > **5 µm**
  - ⇒ Injection force: **10–20 µN** (biologically safe)
  - ⇒ Stable gripping for **10–20 µm** cells
  - ⇒ Natural frequencies > **1 kHz** → robust against lab vibrations
- **Fabrication plan:** 5-mask MEMS process compatible with scalable production

FUTURE PROSPECTS

- **Experimental validation:** Fabrication & microscopy testing in air and fluid
- **Calibration:** Compare in-situ force sensing with external standards
- **Closed-loop control:** Real-time regulation of injecting & gripping forces
- **Scalability:** Multi-cell arrays; curved/compliant target surfaces

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THANK YOU