ME553 - Fall 2008
Microelectromechanical Systems (MEMS)

Course Description: This course provides fundamental knowledge on Microelectromechanical Systems (MEMS) technology and microsystems. The covered topics in this courser include: (a) surface micromachined lateral spring design, (b) piezoresistive & capacitive sensors design, (c) micromechanical resonators design, (d) electrostatic & thermal actuators design, (e) BioMEMS and microfluidic devices design, (f) surface/bulk micromachining, and (g) fundamentals of mechanical measurement and electronics.

Instructor: Prof. Nikos Chronis, Room 3112 G.G. Brown, 763-0154, chronis@umich.edu

Course Web: class material is located on the CTOOLS web site

Class Meetings: Lecture, Wednesday and Friday, 11:30 - 1:00 pm.
Instructor Office Hours, Wednesdays 1:00 pm – 3:00 pm.

Textbooks: No textbooks are required. Teaching materials are provided by the instructor via the course website.

Recommended Books:

- G.T.A. Kovacs, "Micromachined Transducers - Sourcebook," McGraw-Hill, 1998. (available at the bookstore) *Good reference covering all the aspects of MEMS.*
- S.D. Senturia, "Microsystem Design," Kluwer Academic Publishers, 2001 (available at the bookstore) *Very analytical and useful for MEMS design.*
- M. Elwensoek and H. Jansen, "Silicon Micromachining," Kluwer Academic Publishers, 2001 (available at the bookstore) *Good reference book providing an overview of micromachining.*
- S.M. Sze, "Semiconductor Sensors," John Wiley & Sons, Inc, New York, 1994. (reference) *Informative, fundamentals of micromachined sensors are introduced with rigorous analysis.*
- R.C. Jager, "Introduction to MicroElectronics Fabrication," Addison-Wesley, 1998.

Grading:

Homework	20%
Paper Reading	10%
Midterm (Take-Home) Exam	30%
Term Project	40%

Homework Policies:

(1) You may discuss the homework assignments with your classmate. But you are asked to independently prepare your homework answer sheet.
(2) Homework is collected <u>at the beginning of the class</u> on the indicated due date (typically Wednesdays).
(3) In case of unavoidable circumstances, the student may notify the instructor in person, at the end of a class prior to the due date, in order to avoid the penalty.

Paper Reading:
A MEMS related paper will be presented by a group of two students during the first 10 min of each class**.** Students are encouraged to use 5-6 powerpoint slides and they must be prepared to answer questions. A list of suggested papers will be given by the instructor.

Exam Policies:

(1) The midterm exam is an open-book, take-home exam for one-week duration. You need to independently work on it without any help from others.
(2) The honor code must be strictly observed.

Final Project: The final event of ME 553 is a term project carried out by a group of *2* students taking the course. In the project, you are asked to perform quantitative design, modeling, and analysis of a MEMS device of your interest.

(1) Two one-page course project proposal are due on **10/22 (Wed)**. After the project discussion, only one proposal will be selected.
(2) 20-min group presentations are given in class on **12/5 (Fri)** and **12/10 (Wed)**.
(3) A final paper is due on **12/12 (Mon) at 5pm**. The paper should be prepared with a 12-point font size in a single column (**10 page limit including figures**).
(4) *Required Steps:* (a) Pick up a particular MEMS/nano device. (b) Define design objectives (force, displacement, sensitivity, size, and etc…) for the selected MEMS/nano device in connection to a particular application. (c) Propose a new design feature for the selected MEMS. (d) Develop a model that allows you to perform parametric design analysis of your MEMS design. (e) Perform quantitative analysis of the performance of the selected MEMS, (f) Describe experimental techniques and protocols to test the proposed device, (g) Discuss the impact of your design project.

Class Schedule Fall 2008 (Tentative)		**Date and Hw Due**	
1.	Introduction- Overview of MEMS Technology	Wed	9/3
FABRICATION/MATERIALS			
2.	Basic Micromachining Processes and MEMS materials I	Fri	9/5
3.	Basic Micromachining Processes and MEMS materials II	Wed	9/10
4.	Bulk micromachining	Fri	9/12
5.	Surface Micromachining: MUMPS, SUMMIT V Processes	Wed	9/17 (Hw #1)
6.	Polymer Micromachining – Soft Lithography	Fri	9/19
7.	Other MEMS Processes: Micromolding (LIGA), SOI	Wed	9/24
DESIGN/ANALYSIS of MEMS ELEMENTS		Fri	9/26
8.	Beam design 1: moment/deflection	Wed	10/1 (Hw #2)
9.	Beam design 2: common spring configuration torsional deflection	Fri	10/3
10.	Beam design 3: surface micromachined structure reliability	Wed	10/8
11.	Electronics and transducers 1: sensor characteristics	Fri	10/10
12.	Electronics and transducers 2: resistive & capacitive sensor design	Wed	10/15 (Hw #3)
Winter Break			
13.	Piezoresistive transducers	Fri	10/17
14.	Accelerometer design (***Project Proposal Due)***	**Wed**	**10/22**
15.	Project discussion	Fri	10/24 (Hw #4)
16.	Resonator design 2: beam dynamics	Wed	10/29
17.	Resonator design 1: resonant sensors	Fri	10/31
18.	Electrostatic actuators 1: comb drives and parallel plate transducers	Wed	11/5

Take Home Midterm (Assigned on Wed 11/5)

19.	Electrostatic actuator 2: electrostatic instability	Fri	11/7 (Hw #5)
20.	Thermal actuator design 1: bimorph actuators **(Exam Due)**	**Wed**	**11/12**
21.	Thermal actuator design 2: V-shape/hot and cold arm actuator	Fri	11/14

MEMS APPLICATIONS

22.	BioMEMS I– MEMS in Biology	Wed	11/19
23.	BioMEMS II – MEMS in the Medical Field	Fri	11/21

Thanksgiving Break (11/26 – 11/30)

24.	Optical, RF MEMS	Wed	12/3 (Hw #6)
27.	**Project Presentation Day 1**	**Fri**	**12/5**
28.	**Project Presentation Day 2**	**Wed**	**12/10**
	Final Paper Due	**Fri**	**12/12**

ME553 Paper Project Proposal (Sample)
Deadline: November 1 (Wed), 2006

Project Title: *High Displacement Micro-Tweezers using Bent-Beam Thermal Actuation*
Team Members:

1. ____
2. ____

Problem Statement:
Even if MEMS technology has seen some technological maturity in the past decade, there still remains the serious challenge of manipulation at the micro-scale level. This difficulty mainly stems not only from the lack of a micro-scale actuation mechanism that yields sufficient force and displacement, but also from the lack of studies on micro-scale mechanism design. Creating a microscopic actuator device is tricky because of the inability to produce large forces and displacements at this small scale. Manipulation for tasks such as micro-assembly, cell or bacteria handling, and micro-surgical dissection require typically requires a large range of displacements, spanning from tens to hundreds of micrometers, as well as variable forces.

Objectives and Tasks:
1. Propose micro-tweezers that yield large displacement with sufficient force using elector-thermal bent-beam actuation.
2. Perform the design and analysis of the proposed device using a simple analytical model and FEM software, ANSYS.
3. Improve the displacement range of the device by using a two-stage leverage system to amplify the motion of a thermal actuator.

Impacts:
1. The proposed device may find its applications it in micro-assembly and manipulation of MEMS and bio-structures.
2. The proposed actuator design could be applied for a wide variety of MEMS applications requiring a large displacement of motion.

High Displacement Micro-Tweezers using Bent-Beam Thermal Actuation

Irena Gershkovich[1], Peggy Meinhart[2] and Laura Schilling[2]

The University of Michigan Department of Electrical Engineering[1] and Department of Mechanical Engineering[2]

Abstract

This paper describes the design, analysis, and fabrication process of proposed high-displacement micro-tweezers using electro-thermal bent-beam actuation. The design improves upon the displacement range of conventional micro-grippers by using a two-stage leverage system to amplify the motion of a thermal actuator array, making it important in applications such as micro-assembly and manipulation of MEMS and bio-structures. The device measures 746 μm X 1476 μm and achieves a maximum displacement of 220 μm with a gripping force of 15 μN. The micro-tweezers operate at 4.9 Volts and dissipate 117 mW of power.

I. Introduction

As the trend in research and technology development continues to move and expand in the micro-scale direction, the challenge of manipulation at this level becomes a significant concern. This difficulty arises from the unbridged gap between macroscopic and microscopic functioning. Creating a microscopic device that bridges this gap is tricky not only because of its small size but also because of the inability to produce large forces and displacements at this small scale. Manipulation for tasks such as micro-assembly, cell or bacteria handling, and micro-surgical dissection require not only variable forces, but also a large range of displacements, spanning from tens to hundreds of micrometers.

In the past ten years, several micro-manipulation gripper and tweezers designs attempting to combat these challenges have been suggested. One of the most prominent micro-assembly systems is described by Keller and Howe in their publication "Hexsil Tweezers for Teleoperated Mirco-Assembly." These particular tweezers are normally closed requiring input power, to employ thermal expansion actuator beams, and separate the tweezers tips. However, the maximum displacement of these actuator beams is just over 1 μm, and even with an efficient linkage amplification design, the maximum opening distance obtained is 35 μm at the tweezers tips[1]. Another current micro-manipulation tool is the LIGA-microfabricated grippers proposed by Carrozza et. al. This tweezers design is actuated by piezoelectric micro-actuators. By using an amplification method, the tips, initially in an opened position 100 to 120 μm apart, are able to close to 50 μm[2]. Thus, although they have an improved displacement compared with the hexsil tweezers, the end-effectors still can only move in the limited range of 70 μm.

Although the domain of micro-manipulation continues to expand, both in device development and in application, small displacement thresholds continue to limit advancement. In addition, lesser drawbacks such as surface adhesion and electrostatic forces remain problematic since gravitational and inertial forces become negligible in comparison with adhesion forces at this small scale. This paper addresses these issues, focusing mainly on increasing end-effector displacement. We propose a new micro-tweezers design that is predicted to greatly expand the limits of gripping displacement while maintaining reasonable force. The new design will make the micro-tweezers much more versatile, greatly expanding the types, sizes, and shapes of objects able to be manipulated.

II. Approach

The criteria used for selecting an actuation approach for the tweezers design included supply voltage, power consumption, processing complexity, achievable displacement, and force. Electrostatic, piezoelectric, Shape Memory Alloy (SMA) and thermal actuators were compared and bent-beam thermal actuation was chosen because it provides an attractive compromise between the performance metrics mentioned above.

Although electrostatic actuators are simple to fabricate and dissipate very little power, they operate at very high voltages (which are incompatible with standard microelectronic power supplies), provide very low force, and operate non-linearly. Low supply voltages are important in the MEMS field for the integration of micro-mechanisms with sensing and control circuitry, allowing for complete systems on a chip.

The forces generated by electrostatic actuators rarely exceed 10 μN (and are often below 1 μN) in surface micromachined devices. Scratch drive actuators can exert higher forces, but the resulting displacements are commonly less than 100 nm per thrust and require accumulation over many cycles for useful operation. Piezoelectric actuators provide relatively high forces, but also require large power supply voltages, introduce additional processing issues, and require thick films to avoid dielectric breakdown due to the high applied voltages. Shape Memory Alloy (SMA) actuators allow for large forces as well as reasonable supply voltages but dissipate more power and require very specialized processing techniques.

Thermal actuators were chosen due to the fact that they provide relatively large displacements and forces, can operate at low voltages compatible with standard IC devices, and can be fabricated with standard surface micromachining techniques such as MUMPS. Bent-beam actuators were chosen over more commonly used bimorph or pseudobimorph thermal actuators, which rely on differing thermal expansion properties of two elements, because of the attractive compromise they offer in balancing force and displacement[3]. An array of bent-beam actuators was constructed to increase force without compromising displacement. In order to further increase the displacement provided by the thermal actuator array, a micro-leverage system was employed for displacement amplification. This reduces the force available at the tips, but due to the small forces required for micro-manipulation, this is acceptable.

Bent-Beam Thermal Actuator Analysis

Schematic diagrams of a single poly-silicon bent-beam actuator and an array of *n* actuators are shown in Figure 1. A single actuator was designed to produce a desired displacement of 2.5 μm because with this displacement, a reasonable leverage system can be designed to provide a large range of motion at the gripper tips. An array of actuators was then constructed to provide a reasonable gripping forces. The main issues that needed to be considered in designing for the desired displacement and force included power supply voltage, power dissipation in the beam, and the maximum allowable temperature in the beam. It is also important that the supply voltage is below ~10V, not only for compatibility with standard microelectronic power supplies, but also to avoid large electric fields caused by relatively large voltages applied across small distances that could damage the device. For structural integrity, it is also important that the power dissipated in a single beam is on the order of a few milli-Watts and that the average temperate in the beam does not rise above about 800 °C.

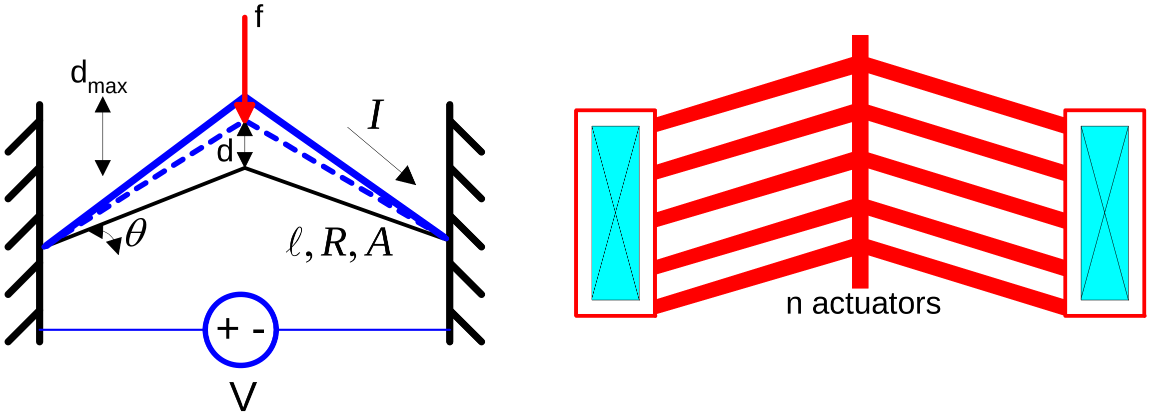


Figure 1. Bent-beam actuator schematic diagram

When a voltage is applied across the anchored ends of the actuator, power is dissipated in the beam, causing thermal expansion in each of half of the beam followed by a rectilinear displacement of the apex. An analytical model[4] was used to relate the maximum displacement of the beam (without an applied loading force) to the average change in temperature and the applied force to the actual displacement (which is reduced by elastic compression caused by the applied force). This model uses geometric and thermal expansion relations and is based on assuming that the change in the angle θ is negligible since the length of the actuator is much greater than the displacement and that the anchored ends are hinged and free to move. This overestimates the force obtained.

The change in beam temperature was related to the power dissipated in one section of the beam by the following relation, where G is the thermal conductance of poly-silicon:

$$Q' = I^2 R = G \Delta T$$

The resistance of the beam can be given by $R_\square$ (20 Ω/□) multiplied by the ratio of the length to width of the poly-silicon beam and the current is determined by the applied voltage and resistance. However, this is an overestimation, so the temperature at the anchored end of the beam was averaged with the temperature at the tip in obtaining the effective temperature change.

The maximum displacement of the beam with no load applied can be given by:

$$d_{max} = \frac{\ell \alpha \Delta T}{\sin \theta}$$

Here α is the coefficient of thermal expansion for poly-silicon, ℓ is the length of one side of the actuator, and θ the designed angle of the beams. The actual displacement is related to the applied force (f) and maximum displacement by the equation:

$$f = 2nAE \sin^2\theta \frac{d_{max} - d}{\ell}$$

Table 1 summarizes the design parameters for a bent-beam actuator array used to activate a single gripper finger. The force at which the actual displacement of the apex is pushed to zero is defined as f_{max}.

Table 1. Design parameters for an actuator array (d_{max} = 2.5 μm, f_{max} = 2.5 mN)

Number of actuators (n)	8
Average ΔT	500 °C
θ	7°
ℓ	163 μm
Beam Cross-sectional Area (A)	2 μm x 2 μm

Analysis of Lever System

The second major component of the micro-tweezers system is a mechanism by which the displacement of the bent-beam actuators can be translated and amplified. In the MEMS world, compliant micro-leverage mechanisms are often used as mechanical amplifiers by transferring an input to an output for achieving mechanical or geometric advantages. Mechanical transformation is achieved by elastic deformation of flexible components of the micro-leverage system. The performance of the system also depends on the input system compliance and the magnitude of the input variables. In our application these refer to the bent-beam actuators.

A very simple leverage design was chosen for reasons of ease of analysis, fabrication, and interaction with the bent-beam actuators. This type of lever arm was designed and analyzed by Su and Yang in 2001[5]. A general representation of a single stage of the leverage system is seen in Figure 2. An input force and displacement are given a specified distance, L, from a fixed anchor introducing bending in the elastic beam. Geometric relationships require that the output displacement a given distance, l, from the anchor will be a multiple of the input displacement. Operating under the assumption that the lever arm is sufficiently stiff to resist any bending, the ideal displacement amplification for the single stage lever arm will just be the ratio between the output and input lengths (L/l). Displacement effects due to compression of the spring were calculated and determined to be negligible as compared to displacement due to the geometric amplification. Therefore, when calculating the output displacement of the lever arm relative to the input displacement, the ideal amplification factor was used.

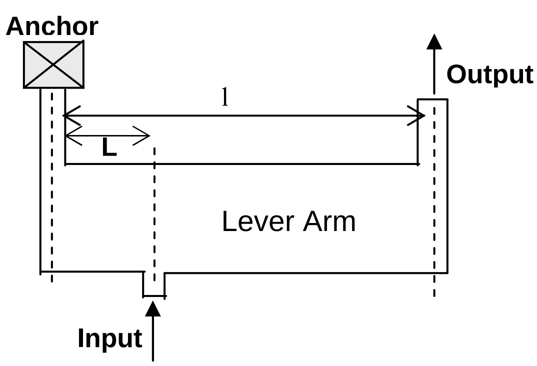


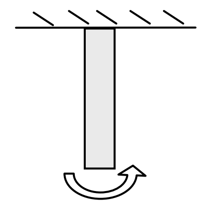
Figure 2. Micro-leverage System

It was determined that in order to most successfully achieve our desired displacement, two stages of the simple lever arm should be used, the output of the first stage serving as the input for the second stage. The two stages would be identical in structure and function, but have different dimensions and therefore amplification factors. The overall amplification factor for the leverage system is then the product of the amplification factors for the individual stages.

Other than the degree of displacement amplification, other design considerations for the leverage system included maintaining a sufficient gripping force at the gripper tips, minimizing the strain in the springs, minimizing the external force applied to the bent-beams by the leverage system, and geometric considerations. All issues were addressed through the use of equilibrium equations and/or free beam analysis.

Maintaining a sufficient gripping force at the gripper tips was also an issue. Due to equilibrium of moments about the anchor and the lever having a longer moment arm, the output force will decrease by the same factor that the displacement increases. Therefore, the leverage system was designed in a manner so that the desired displacement was achieved while preserving adequate gripping force for micro-object maneuverability.

Secondly, while obtaining the desired displacement of the gripper tips, it was required that the springs (beams attached to the anchors) exist in a state of strain less than 1% to ensure non-failure. The upper bound of 1% is based on the generally accepted upper bound for poly-silicon. Given a reasonable input displacement and force, the strain in the spring was calculated by assuming that it was a free beam with a moment applied at the free end (see Figure 3). The moment is generated by the input force, from either the bent-beam or from the previous leverage arm, being applied a certain distance from the spring. Dimensions of the spring were changed so that the strain stayed below 1%.



$$\varepsilon_{ma} = \frac{aF_{input}L}{2EI}$$

Figure 3. Spring Strain

The design of the springs also had an influence on the overall spring constant for the leverage system. This value was important because it is directly related to the resistive force that is applied to the bent-beam actuators. The input force from the bent-beam is the difference between the maximum possible bent-beam force and the resistive force from the leverage system. Therefore, a high resistive force would limit the input force and displacement possible from the actuator. The rotational spring constant for each of the springs was calculated and the combination of the two springs led to the overall spring constant for the system.

Finally, geometric factors were considered due to size, weight, and placement issues. As was previously stated, the lever arms for the leverage systems needed to be sufficiently stiff as to resist any bending due to the input force. The lever arm was considered to be a free beam of the length from the anchor to the point of input. The input force was applied to the end to determine the amount of bend in the lever arm. The width of the lever arm was increased until the displacement due to bending was less than 0.01%. Considering the lever arm to be fixed at one end is a conservative assumption. Since a great deal of the bending will occur in the spring the calculated amount of bending in the lever arm is an overestimation. Due to the extreme length of the lever arms, we also wanted to make sure that they would not experience an excess amount of strain due to their own weight. To check this condition, the lever arms were again assumed to be fixed, free beams. Any geometric simplifications consisted of adding width but not thickness to the beam. Using the density of poly-silicon and the volume of the beam, its weight was calculated and then an equivalent force was applied to the free end. Again this is a worst-case scenario. It was found that the weight of the lever arms did not create sufficient strain to cause failure. The same methods were applied to the springs, but the force applied at the ends of the springs was the sum of the weight of the spring and the weight of the lever arm. Our last consideration involved the placement of the lever arms with respect to each other and with respect to the bent-beam actuators. It was necessary to place the components in a manner so that there was no physical interaction when the bent-beams were fully activated.

The final design for the leverage system required a balance between each of the previous factors discussed. After each of these issues were addressed and satisfied, it was our belief that a successful design for the leverage system was determined.

III. Proposed Design

Using the array of bent-beam thermal actuators and the two-stage micro-leverage mechanism, a new tweezers design has been devised. A functional diagram (not drawn to scale) of the proposed design is shown in Figure 4. The device, with a normally closed end-effector, operates on the principle that an electric current is passed through a bent-beam array, which is anchored at both ends. Thermal expansion due to joule heating pushes the apex outward in a rectilinear motion. The apex then pushes against a two-stage micro-leverage system that amplifies the displacement and creates much larger motion at the gripper tip. The springs on the micro-leverage mechanism will return the gripper to a normally closed position when not in use. To allow for more flexibility in handling objects, each gripper arm can be activated independently. The second stage lever arms are angled to produce a sleek design allowing for manipulation in small, irregular spaces. In addition, the gripping surface profiles are designed with 25 teeth to utilize protrusions for grasping and decrease the area of surface contact to minimize surface adhesion forces. The entire tweezers structure is fabricated from phosphorous doped poly-silicon. Once fabricated, the tweezers will be attached to an x-y positioning stage for precise manipulation of micro-objects.

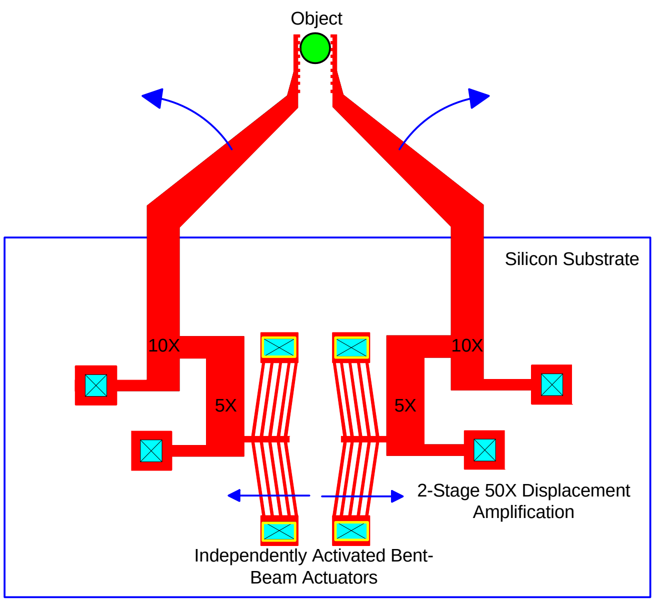


Figure 4. **Proposed gripper design.**

IV. Results

Combining the analysis of the bent-beam actuators and the leverage system focusing on displacement amplification, a final design for our micro-grippers was determined. When power is supplied to the bent-beams, the resulting motion forces the gripper tips to be moved apart from each other, allowing them to be positioned around a micro-object. To grasp the object, the power is removed from the bent-beam actuators and the lever arms return to a normally closed position. The shape and size of the object to be grasped resists full closure, generating the gripping force. The object can then be manipulated. Therefore, the only time that power is required in the system is during positioning of the object between the gripper tips. The design of this system brings about a minimum size object that can be manipulated. If the object is not big enough to resist the lever arm motion back to its original position, then there will not be enough gripping force to grasp and move the object.

A scaled mask of the design and corresponding dimensions are seen in the Appendix. Table 2 contains relevant information regarding output displacement as well as force and input requirements. In addition, a comparison between the maximum displacement at the tweezers tips for our design and current designs is found in Table 3.

Table 2. **Gripper Performance**

Voltage (V)	**4.9**
Power (mW)	**117**
Max Disp of Tips (μm)	**220**
Gripping Force (μN)	**15**

Table 3. Displacement Comparison

	Maximum Displacement at Tips
Berkeley Hexsil Tweezers (1997)	**35 μm**
LIGA Grippers (1998)	**70 μm**
Proposed Micro-Gripping System (Ideal)	**220 μm**

V. Fabrication and Layout

The device will be fabricated using a slightly modified MUMPS surface micro-machining process. The two major modifications made to the standard MUMPS process involve adding a supercritical CO_2 drying step to the standard HF release etch to avoid stiction issues, and including a bulk micro-machining step to etch a groove in the silicon substrate so that it can be easily and precisely broken off from below the gripper tips[6]. Figure 5 shows a top view and cross sectional view of a bent-beam actuator.

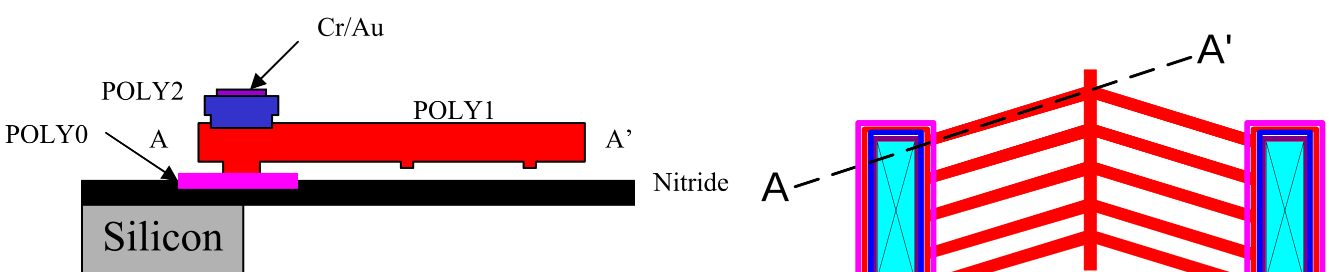


Figure 5. Cross section along bent-beam actuator

The standard MUMPS process begins with the blanket deposition of a 600 nm Nitride layer over a (100) Silicon substrate. After the deposition and patterning of a standard 500 nm polysilicon layer (POLY0), a 2 μm oxide layer is deposited by low pressure chemical vapor deposition (LPCVD), patterned and 750 nm deep dimples are etched by Reactive Ion Etching (RIE). The oxide layer is then patterned and an RIE etch is performed to provide a POLY1 to substrate anchors. A 2 μm layer of poly-silicon is then deposited by LPCVD followed by the deposition of a PSG layer and a 1050°C/1hour anneal for doping. The first poly-silicon (POLY1) layer is then lithographically patterned and an RIE etch is performed. A 0.75 μm second oxide layer is then deposited and patterned twice to allow for contact between POLY2 and POLY1 as well as for a POLY2 to substrate anchor. The second poly-silicon layer (1.5 μm thick) is then deposited, doped and patterned as described for the POLY1 layer. A Cr/Au metallization layer is then deposited and patterned by lift-off to provide for electrical contacts. Typically, a standard HF etch is then performed to release the structures by removing the sacrificial oxide layers; however, to avoid stiction due to the large length of the gripper fingers, a supercritical CO_2 drying process is incorporated.

The bent-beam actuator array structures along with the gripper fingers and micro-leverage mechanism are constructed by patterning the 2 μm layer of 20 Ω/□ phosphorus-doped poly-silicon (POLY1). The second layer (POLY2) of similarly doped conductive poly-silicon is used to provide an electrical contact from the bent-beam to the Cr/Au metallization layer which is deposited and then patterned by lift-off. A standard MUMPS bonding pad is constructed using POLY0, POLY1, ANCHOR1, POLY2 , Poly1-Poly2 via, and METAL as shown above. Dimples are used along with the critical CO_2 release to avoid stiction problems. Etch holes are also provided to allow the etchant to readily reach the oxide under the poly-silicon. The dimensioned system layout is shown in the Appendix, all numbers are in units of microns.

VII. Discussion

The large displacements we are predicting from this new device design will vastly improve the micro-gripping and micro-manipulation applications. Not only do we predict that our device will achieve displacements two to three times larger than existing tweezers techniques, but we anticipate that the device will also maintain gripping forces comparable to that of current designs while employing acceptable power.

Apart from an improvement in end-effector displacement, one of the greatest attractions of our system is its flexibility. The dimensions and size of the bent-beam array can be manipulated to increase or decrease the maximum displacement or force produced by the unloaded beams. In addition, the length of the gripper arms can be adjusted to increase or decrease the largest amplified output force and displacement that can be obtained. Figure 6 shows the relationship between the variable parameters of the device and the resulting maximum force and maximum displacement. It can therefore be seen that customized devices may be fabricated for specific applications based on the forces and displacements desired.

The applications of a flexible gripping design with large maximum displacements are many, and more applications continue to be discovered. For example, these gripping advancements will continue to be useful in micro-assembly for various micro-systems such as optical elements and micro-circuits. Also, now that maximum displacements of over 200 μm are obtained, this device can be used for selective handling of samples such as cells and bacteria, which have diameters ranging between 100 and 200 μm. Micro-tweezers applications also include, among other things, sample preparation for electron microscopy, micro-surgical dissection, and micro-telerobotics.

VIII. Conclusion

In conclusion, we have employed bent-beam actuation and microleverage amplification to design a new micro-gripping device, which is predicted to be a successful and useful improvement in current micromanipulation tweezers designs. Our new design will broaden micro-assembly capabilities, predicted to produce maximum displacements of 220 μm. By increasing the possible displacement range of gripper tips, providing greater force capacity, enabling independent finger actuation, and introducing device flexibility, larger, more awkward objects can be manipulated and precisely positioned. The development of this design will greatly expand the growing field of micro-gripping applications.

The maximum displacement and force given in this paper are ideal values and, in the future, will require validation by actual fabrication and testing of the proposed tweezers device. Also, since it is important for a micro-gripping device to be able to sense the force that is being used to secure an object, future work includes incorporating poly-silicon piezo-resistive strain gauges into the grasping fingers, providing force feedback sensing. With the aid of electronic read-out circuitry, the resistance measured across the strain gauge would indicate the gripping force being applied. These additions will increase our understanding of the tweezers device, enhancing its functionality and pinpointing its limitations, leading to further improvements in gripping technology in the future.

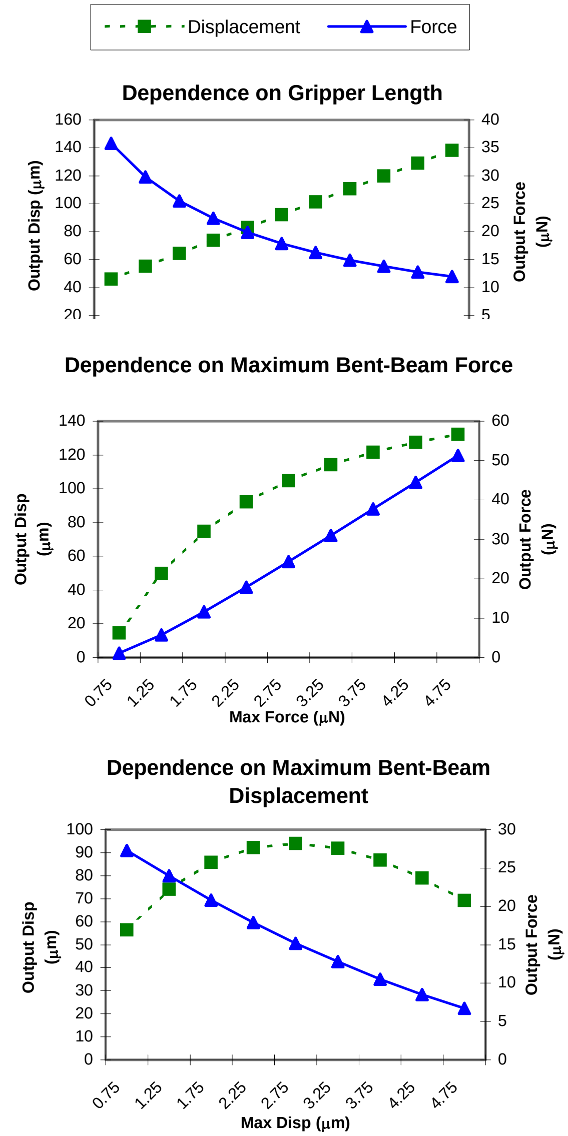


Figure 6. Variation in Output Performance

References

[1] C.G. Keller, R.T. Howe, "Hexsil Tweezers for Teleoperated Micro-Assembly," *MEMS '97, Proceedings, IEEE., Tenth Annual International Workshop on Micro Electro Mechanical Systems*, pp. 72-77, 1997.

[2] M.C. Carrozza, A. Menciassi, G. Tiezzi, P. Dario, "The Development of a LIGA-Microfabricated Gripper for Micromanipulation Tasks," *J. Micromech. Microeng.,* 8, pp. 141-143, 1998.

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