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Sergey Y. Yurish



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Design and Simulation of a Microgripper with the Ability of Releasing Nano Particles by Vibrating End-Effectors

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Abstract: this paper investigates the design and simulation of a new type of microgrippers which is able to release nano particles by vibration. After picking and transferring the object to the desirable substrate electrothermally, an electrostatic oscillation system (comb-drive) generates vibration at the gripper arms that facilitates the release process by taking advantage of inertial effects.
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Keywords: Micro electro mechanical systems **(**MEMS), Vibrating microgripper, Nanohandling, Active release technique.

1. Introduction

Due to continuous progress in the field of microassembly, microgrippers have become inevitable options for micromanipulation and nanohandling. High precision, robustness and reliability are characteristics that enable microgripper to be employed in nanohandling to pick and place nano particles especially nanotubes/wires/fibers.

Since microfabrication process is able to fabricate complex systems, researchers have employed different actuation to build various microgrippers in science and industry. Electrostatic and electrothermal are suitable actuations that have been used in most researches. Kim et al. [2] developed a polysilicon electrostatic comb-drive microgripper. Anderson et al. [3] designed more mechanically stable, electrothermal three beam microgripper with high gripping force to pick and place an as-grown carbon nanotube. In addition to the three beam microgripper, Carlson et al. [4] investigated an Asymmetric RibCage (ARC) gripper which was able to provide more gripping force than three beam due to a rigid end effector.

Since the handling objects are in the range of micrometer and nanometer, interactive forces such as Van der Waals force, surface tension force and electrostatic force between micro/nano particles and gripper surface become more dominant [5]. As a result, it is easy to pick up an object using adhesion forces but the release process is very difficult [6].

To release objects rapidly and accurately, several strategies have been proposed in the past decade.

Aray et al. [5] analyzed the balance of the adhesion forces between the objects and proposed methods to reduce adhesion forces based on the micro physics and also fabricated a gripper arm with rough surface to overcome the adhesion. Kim et al. [7] coated the gripper arms with chemical materials to facilitates the release process.

Generally there are two techniques for releasing process: passive release and active release [8].

Passive release method depends on the adhesion forces between the micro object and substrate to detach the object from end-effector [8, 9].

Active release method is independent of the substrate and it detaches object from end-effector without touching substrate. Brandon et al. [8] designed a novel electrostatic microgripper integrated with a plunging system to impact micro object to gain sufficient momentum to overcome the adhesion force.

Vibration is a strategy to release an object. In fact, vibrating the end-effector generates enough inertial force to overbalance the adhesion forces [6]. Sinan et al. [10] fabricated a gold coated silicon micro beam to pick the micro object and employed vibrating the beam to overbalance adhesion to achieve the release. Chen et al. [9] designed and fabricated a micro manipulation system including a MEMS-based microgripper fixed on a PZT ceramic. The electrostatic microgripper was able to pick the micro object and vibrate the end-effectors horizontally (in-planely) and PZT vibrated the microgripper vertically. So the compound vibration takes the advantage of inertial effects to overcome adhesion forces.

In this paper, we investigate and design a microgripper that is able to grab and pick the nano objects from the substrate electrothermally, transfer to the desirable substrate and release the object by vibrating the end-effectors. An electrostatic comb drive system which oscillates at resonant frequency along x-direction (in-planely) provides the vibration to detach the object from the end-effector. Fig. 1 shows the schematic drawing of the microgripper.

2. Design Consideration

2.1. Actuation

Chevron or V-shaped bent beam actuator requires low driving voltage, produces larger force and generates large displacement through motion amplification [7], hence in this work is employed as an actuator. The electric current that passes through the beams, generates heat due to resistive heating. The thermal expansion of the beams causes that the apex to move downward (along x-direction) considering that the beams are located between two anchor points. It results in closing the gap. Table 1 shows the microgripper dimensions.

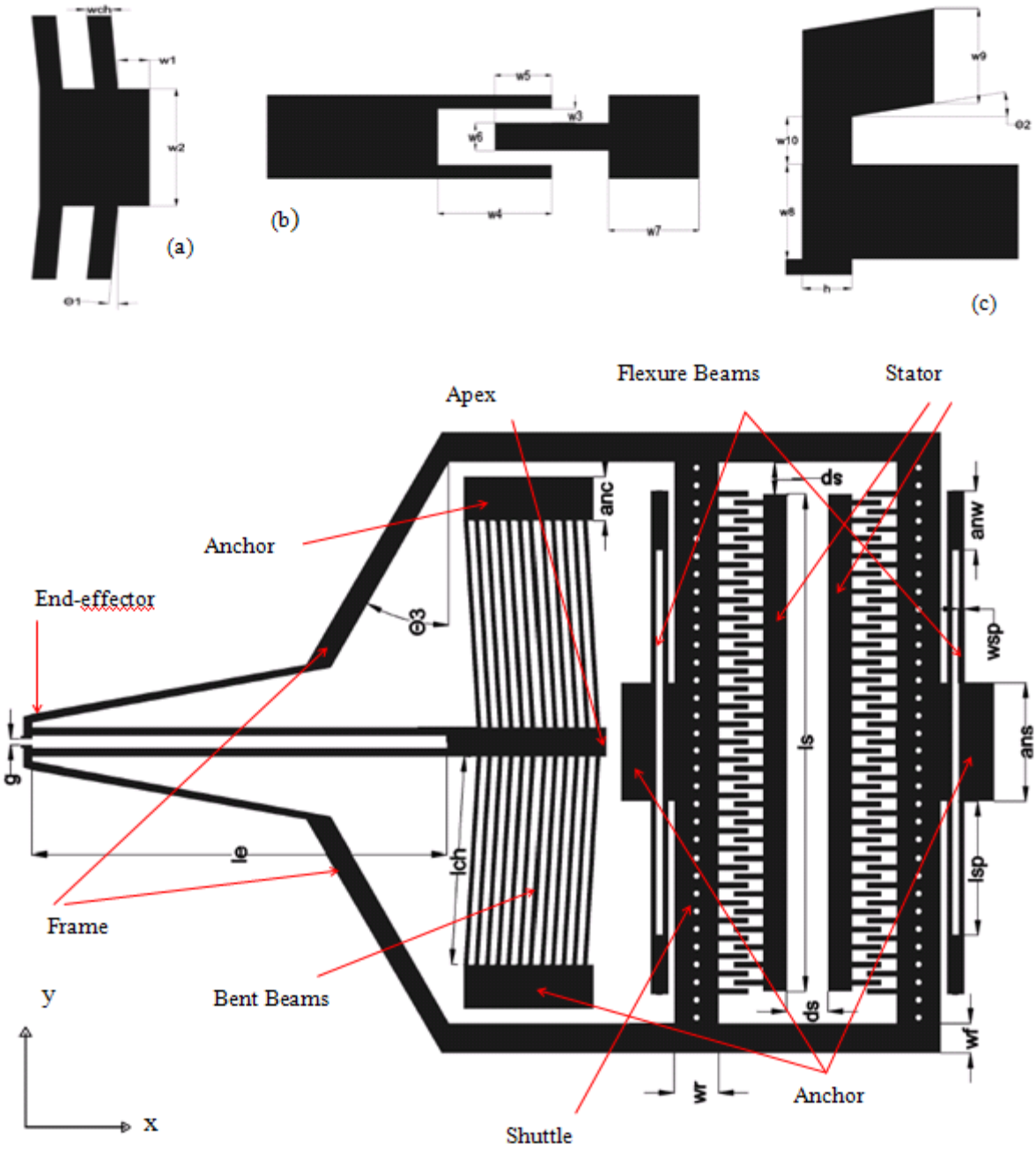


Fig. 1. Schematic diagram of microgripper:
a) Chevron actuator details; b) Comb-drive details; and c) End-effector details.

Table 1. Geometrical parameters used in this work.

Frame		**Comb drive**		**Chevron actuator**		**Flexure beam**	
Θ2 (°)	10	Ls (мм)	158	Θ1 (°)	4	Lsp (мм)	45
Θ3 (°)	30	ds (мм)	15	Wch (мм)	1.2	Wsp (мм)	2
g (мм)	1.4	Wr (мм)	15	Lch (мм)	70	anw (мм)	10
le (мм)	140	W7 (мм)	8	W1 (мм)	1.4	ans (мм)	20
Wf (мм)	8	W3 (мм)	1	W2 (мм)	8	-	
W8 (мм)	2	W4 (мм)	10	Anc (мм)	16	-	
W9 (мм)	2	W5 (мм)	5	t (мм)	2.5	-	
W10 (мм)	1.1	W6 (мм)	1.2	d (мм)	1	-	
h (мм)	3	ncd	34	nch	12	-	

In Table 1 t is microgripper thickness, d is distance between microgripper and substrate, ncd is number of comb fingers in each comb drive system and nch is number of chevron actuator bent beams.

Due to thermal conductivity of polysilicon is much larger than air and heat lost through radiation is considerable at high temperature [11] , we neglect the heat dissipation through convection and radiation. The material properties of poly silicon which are used in simulations are listed in Table 2.

Table 2. Material properties of polysilicon.

Material Properties	Value	References
Young's Modulus (GPa)	160	[15]
Poison Ratio	0.22	[15]
Electrical resistivity (Щ-m)	5.1×10^{-5}	[17]
Thermal Conductivity (W/m.k)	30	[16]
Thermal Expansion Coefficient (1/k)	2.7×10^{-6}	[16]
Density (Kg/m3)	2300	[14]

Since high temperature is not sustainable for some nano particles [3], we try to keep temperature at low values at the end effectors as possible. In this regard, we limit the temperature below 200 °C at the middle of the chevron actuator (Fig. 2) because in this case the microgripper is capable of closing the gap larger than 1 μm (g = 1.4 μm) and the temperature at the end-effector is below 170 °C.

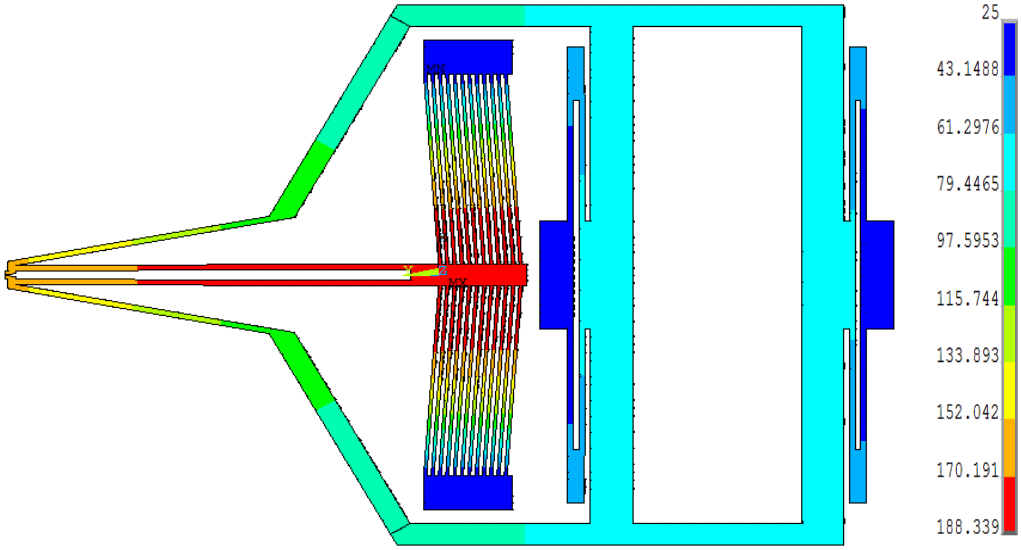


Fig. 2. Thermal distirbution for case 2 (Θ2 = 10, Θ3 = 30). Tempreture is maximum at the middle of the chevron actuator.
Vin = 1.4 V.

2.2. Frame

We employ the frame to amplificate and convert x-directional motion of the chevron actuator to y-directional motion at the end-effectors. Frame needs to be mechanically strong to provide high gripping force, on the other hand, it has to close the gap at the temperatures below 200 °C in the

chevron actuator. Angles Θ2 and Θ3 play crucial roles in the frame stiffness. To find the desirable frame, we investigate different angles (cases) effects on the frame stiffness by FEA simulation (Fig. 3). Table 3, shows angles of each case.

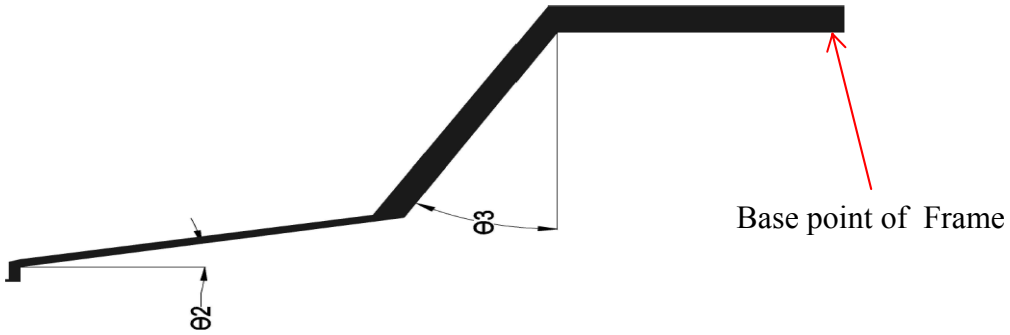


Fig 3. Two crucial angles of the Frame.

Table 3. Angles of each case applied in simulations to find desirable frame.

	Θ2 (degree)	**Θ3 (degree)**
Case1	10	45
Case2	10	30
Case3	10	15
Case4	10	0
Case5	0	30
Case6	5	30

In the simulations, the pressure is applied to the end-effectors and increased to the extent that the end-effectors start to move backward. Fig. 4 shows the end-effector deflection versus force for each case. The slope of each curves indicates the compliance (the inverse of stiffness is compliance) of the frame at each case.

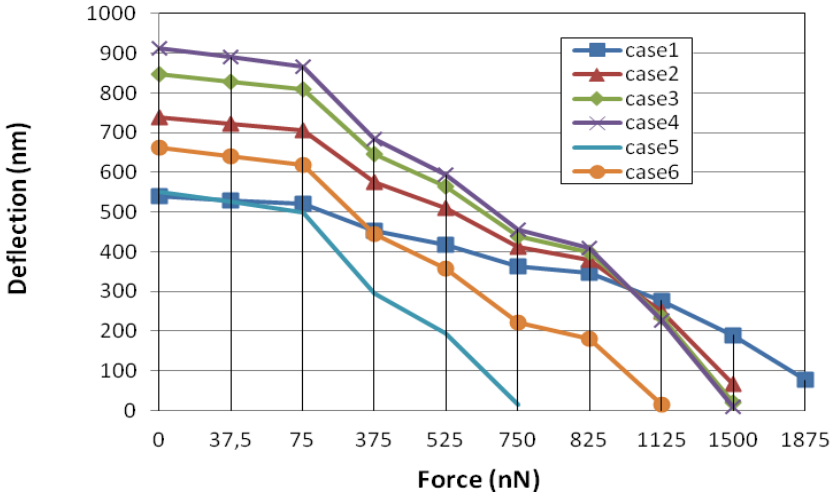


Fig. 4. The end-effector deflection versus force for each case.

Case 1 is the stiffest frame but it is not able to close the gap at temperature below 200 °C. The minimum stiffness belongs to case 5 therefore it is able to generate low gripping force. Case 2 has acceptable behavior because it is stiff enough to generate forces at the range of 1 μN and it can close the gap whereas the temperature in the chevron actuator is less than 188 °C and at the end-effector is less than 170 °C (see Fig. 2). Note that it is necessary for each gripper arm to deflect more than half of the gap to close the gap firmly and produce gripping force [3]. Fig. 5 shows the end-effector deflection for case 2.

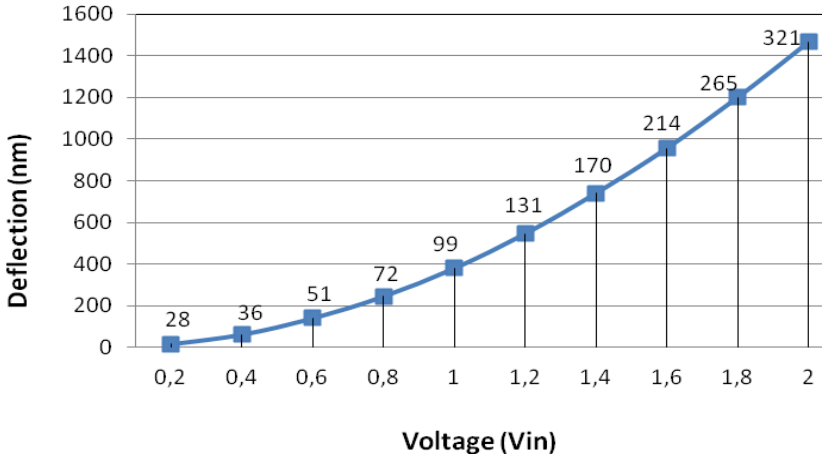


Fig. 5. The end-effector deflection versus voltage for case 2. The numbers in the figure indicates the end-effectors temperature (°C).

Since the best amplification at the frame occurs when the base point of the frame is immovable, the flexure beams are designed to avoid moving the base point of the frame largely along the x-direction at the gripping phase (dimensions in Table 1).

3. Vibrator

At the release stage, the free end of object is placed on the substrate, if the adhesion between object and substrate is larger than the adhesion between object and gripper surface, it is released. Otherwise, by vibrating the end-effector, the adhesion force between particle and gripper arm decreases due to inertial effects [9]. The interdigited-finger comb drive structure is one of the earliest surface micromachined resonator design which commonly used in MEMS devices such as micro gyroscope, micro accelerometer and resonators .As an example, Clark [12] designed and fabricated an interdigited comb fingers that operated as a micromechanical resonator. When AC excitation voltage with frequency close to the fundamental resonant frequency of the micro resonator was applied, the micro resonator began to oscillate.

In this regard, we employ the interdigited comb drive system with two flexure beams that suspend the shuttle 1 μm above the substrate and enable the shuttle to oscillate along x-direction parallel to substrate. The frame amplificates and converts the shuttle oscillation to the vibration along y-direction at the end-effectors.

By Modal FEA analysis, we are able to find the resonant frequency (F_r) in which the shuttle oscillates along x-direction parallel to the substrate. In order to make oscillation, two voltage signals at this frequency (F_r) are applied to the stators to excite the oscillation (the shuttle is ground). Fig. 6 shows

these pulse signals. Additionally Fig. 7 indicates the boundary conditions at gripping stage and vibrating stage. We assumed the substrate temperature is constant at 25 °C.

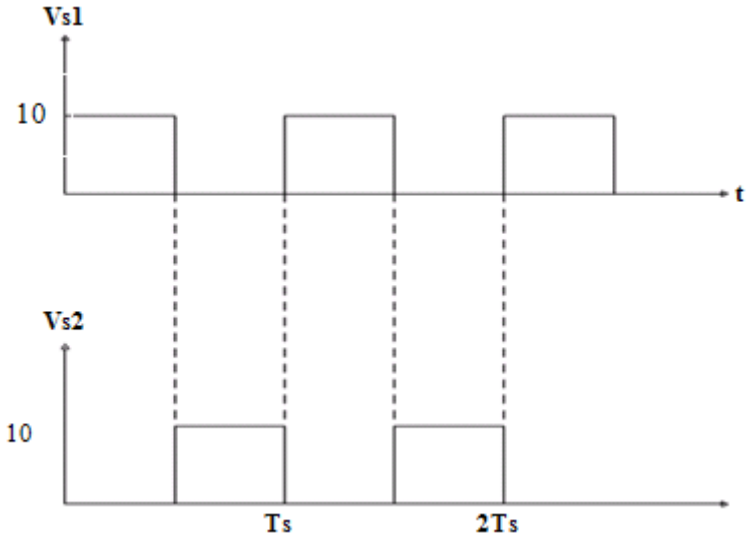
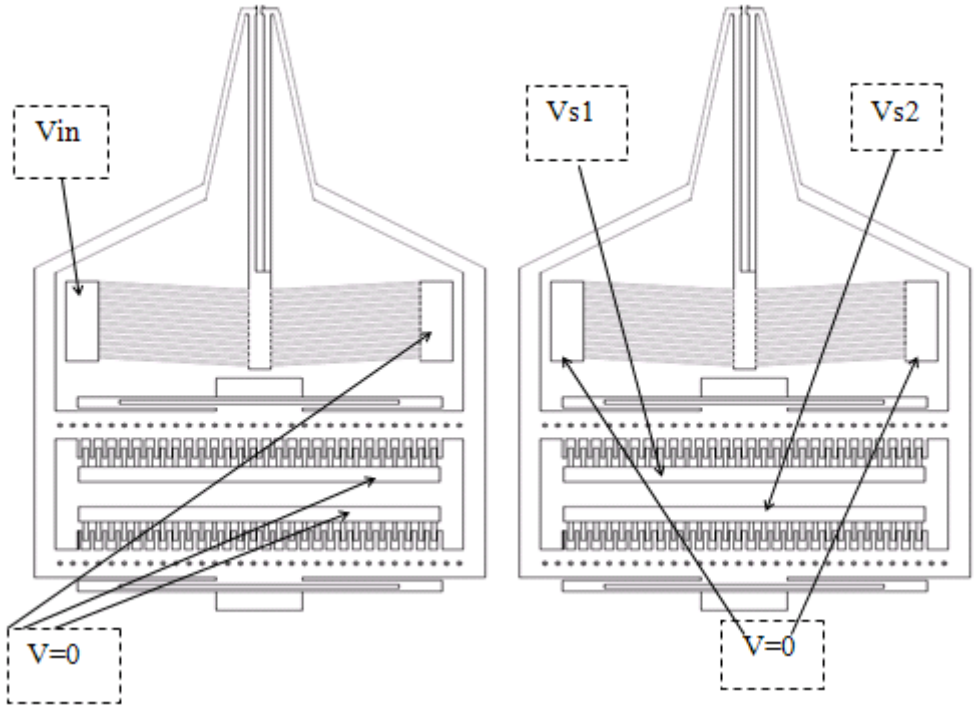


Fig. 6. The voltage signals applied to the stators, (T_s =1/F_r).



(a) (b)

Fig. 7. Boundary conditions at a) gripping stage b) releasing stage.

The x-direction electrostatic force on each comb tooth is given by [2]:

$$F_{el} = \frac{\varepsilon_0 t V^2}{W_g}, \quad (1)$$

where ε_0 is the air permittivity, t is the thickness of comb drive and w_3 is the gap between stator teeth and rotor teeth.

For precise investigation, one interdigited comb finger is simulated to estimate the electrostatic force and compare the results with Equation 1.

Fig. 8 shows a cross-sectional view of the simulation. A spring is connected to the rotor for electrostatic force estimation. It means by applying voltage across the rotor and stator, the electrostatic force attracts the rotor toward the stator, it results the spring to elongate along x-direction. By calculating the strain and stress of the spring, the force is estimated. Fig. 9 shows the comparison between theoretical and simulation results.

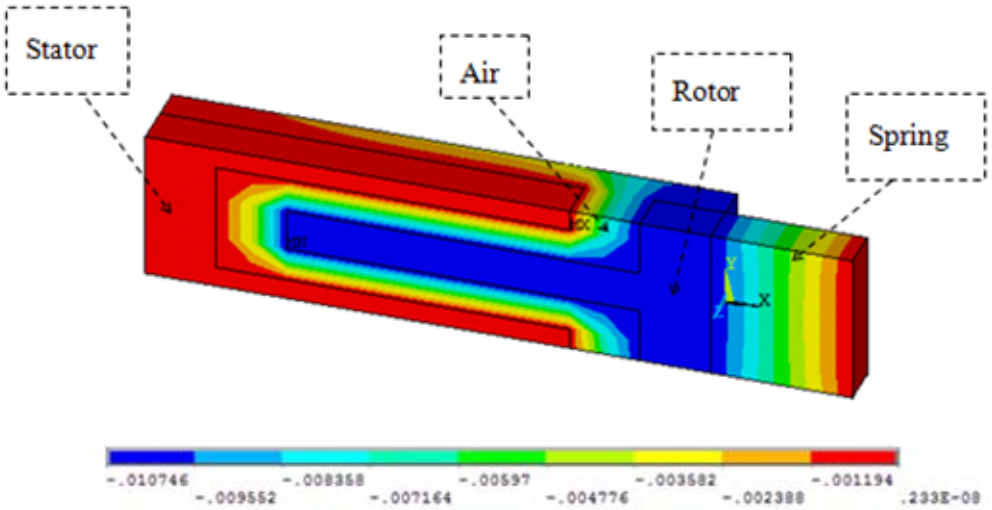


Fig. 8. One interdigited comb finger electrostatic simulation at Vs =10 V.

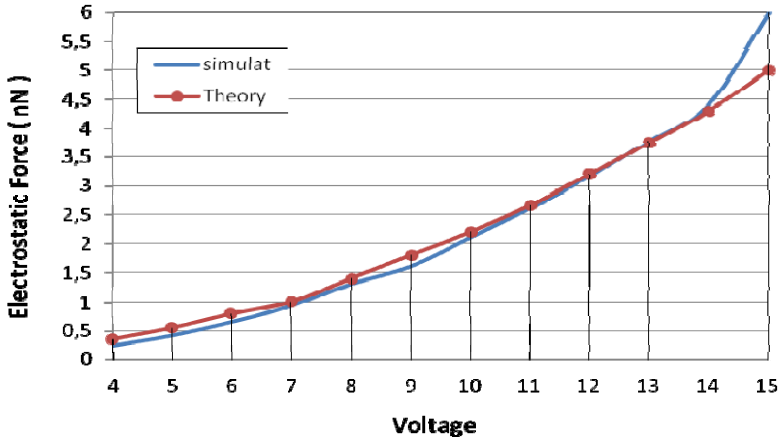


Fig. 9. Electrostatic force for each comb finger.

Since the oscillation is parallel to the substrate, the sliding damping plays an important role. Sliding damping factor is given by [13]:

$$c_{slide} = \mu_{eff} \frac{A}{d}, \tag{2}$$

where A is the overlap area of the shuttle and the substrate, d is the gap between shuttle and the substrate. Table 4 shows damping parameters briefly.

Table 4. Damping parameters.

μ (MPa-s)	1.86×10^{-11}*	Air viscosity
л (мм)	6.7×10^{-2}*	Gas (air) mean free path
C_{slide}	0.115	Sliding damping factor

*[1]

The effective viscosity is given by [13]:

$$\mu_{eff} = \frac{\mu}{1 + 2k_n + 0.2k_n^{0.78}e^{-\frac{k_n}{10}}} \tag{3}$$

where K_n is the Knudsen number, which is calculated by [13]:

$$K_n = \frac{\lambda}{d} \tag{4}$$

Note that the sliding damping between the shuttle and substrate is much more than damping between comb drive fingers, thus it is neglected.

At last, Harmonic FEA analysis is employed to estimate the end-effectors and oscillator (shuttle) vibration amplitude at the resonant frequency. Table 5 shows value of resonant frequency and vibration amplitude for each case. Harmonic simulation results for our choice (frame case 2) is in Fig. 10.

Table 5. Resonant frequency and end-effector vibration amplitude at this frequency for each case.

	Frequency (kHz)	**Amplitude of vibration (nm)**
Case1	183	11
Case2	172	18
Case3	160	22
Case4	150	25
Case5	183	15
Case6	178	17

4. Proposed Fabrication Process Flow

A common polysolicon surface micromachining with a photolithographic line width of 1μm is used to fabricate the gripper. An outline of the proposed fabrication process with detailed information is given in Fig. 11.

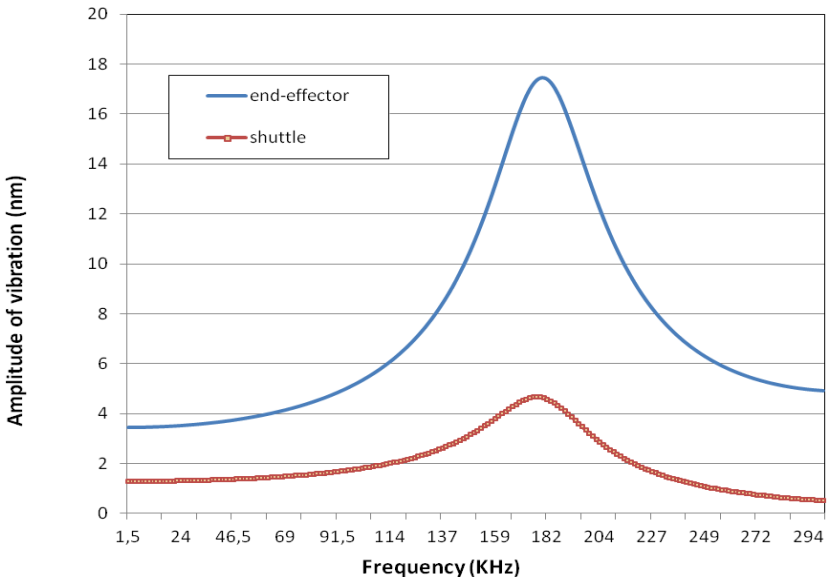


Fig. 10. End-effector and shuttle vibration amplitude versus frequency for case 2. Resonant frequency (Fr) = 172 kHz

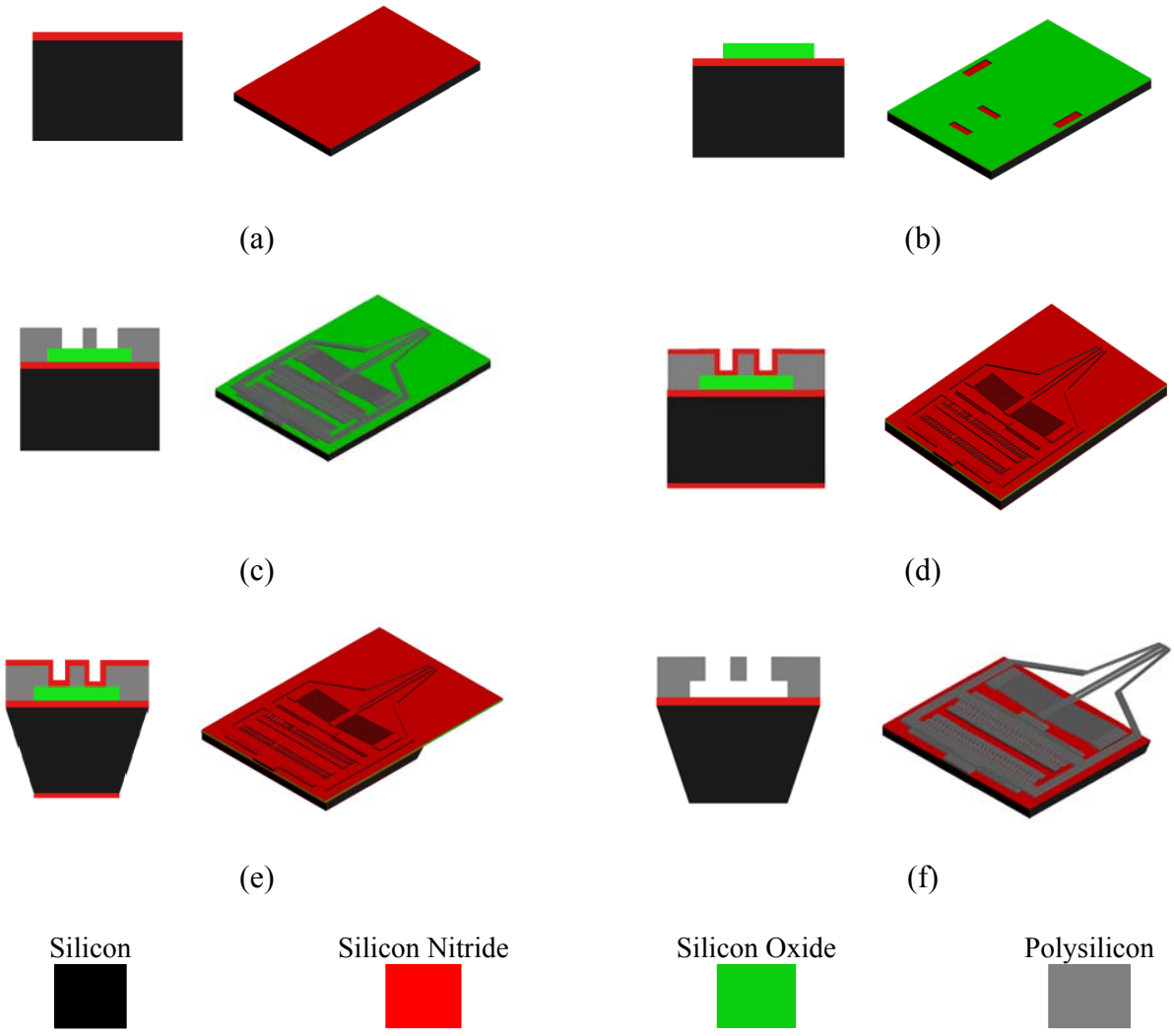


Fig. 11. Fabrication process. At each part, left picture is cross-sectional view and the right picture is general view.

a) Silicon nitride thin film is deposited on top of the Si wafer using LPCVD.
b) Silicon oxide layer is deposited and patterned to form the anchors.
c) Polysilicon is deposited and patterned using photolithography and RIE.
d) Pilicon nitride thin film is deposited on both sides of the wafer using LPCVD.
e) The back side silicon nitride is patterned lithographically and used as an etch mask for anisotropic potassium hydroxide etch of the silicon wafer carrier with the buried Sio_2 as an etch stop.
f) The silicon nitride is removed in phosphorus acid and finally the microgripper structure is released with hydrofluoric acid etch of the sio2 [3].

5. Conclusions

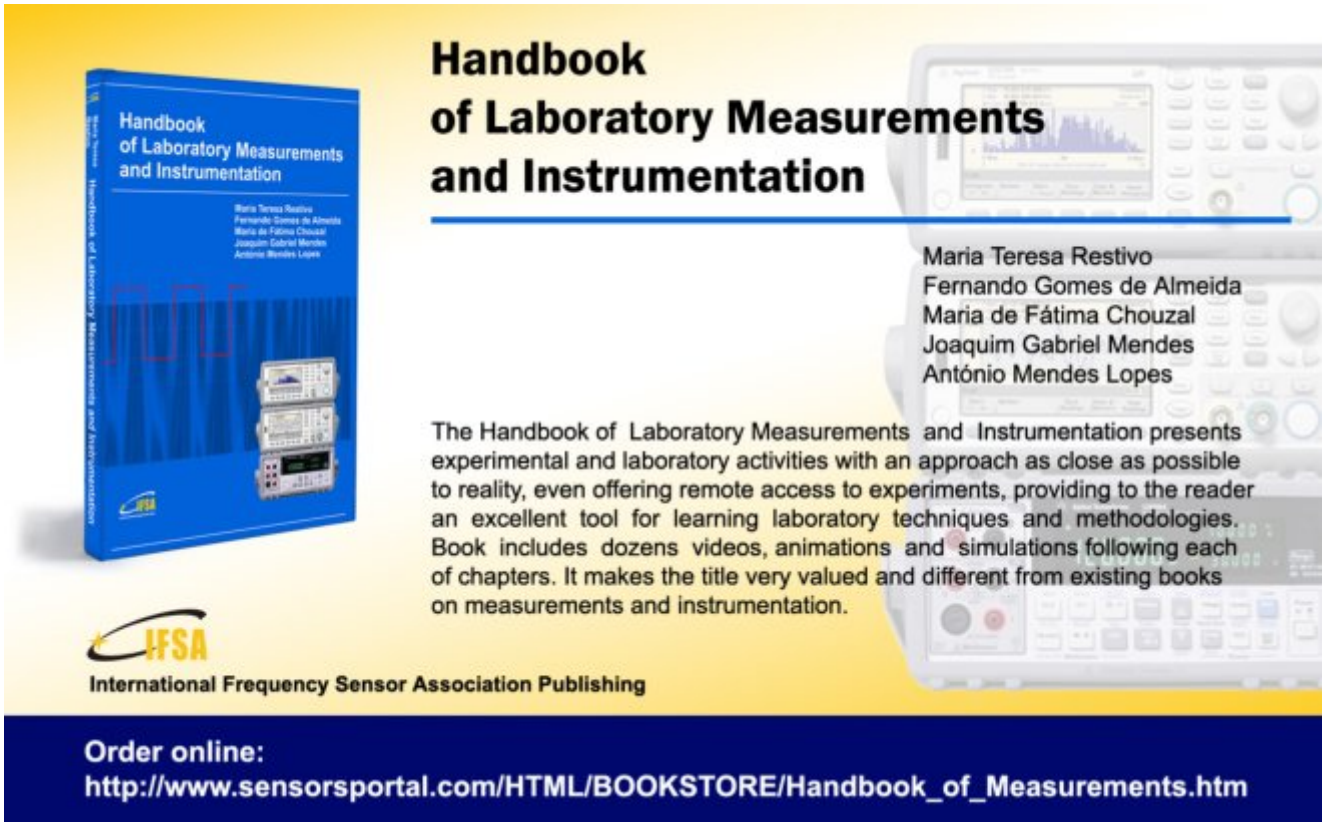
In this paper, we designed and simulated a microgripper that was able to grasp nano objects electrothermally and release it by active release technique. Different cases (angles) for frame was simulated to find desirable stiffness. So, the electrothermal chevron actuator with frame case 2 (Θ2=10, Θ3=30) showed appropriate functionality at the gripping stage. At this stage, chevron actuator worked at Vin=1.4 V, while the temperature at the middle part of chevron actuator was less than 188° C and at the end-effectors was less than 170° C. Each gripper arm deflection was 738 nanometers. At the release stage, we employed the interdigited com-drive system to make oscillation and the frame converted it to vibration at the end-effectors. Modal and Harmonic FEA simulation showed that the resonant frequency (F_r) for our choice (frame case 2) was 172 kHz and the amplitude of vibration for the shuttle was 5.2 nm and for the end-effector was 17.2 nm.

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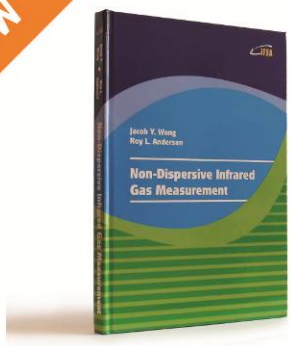
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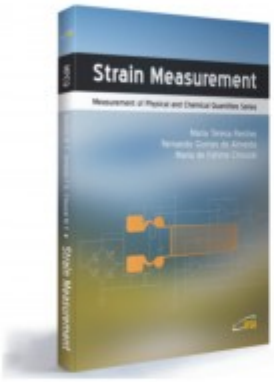
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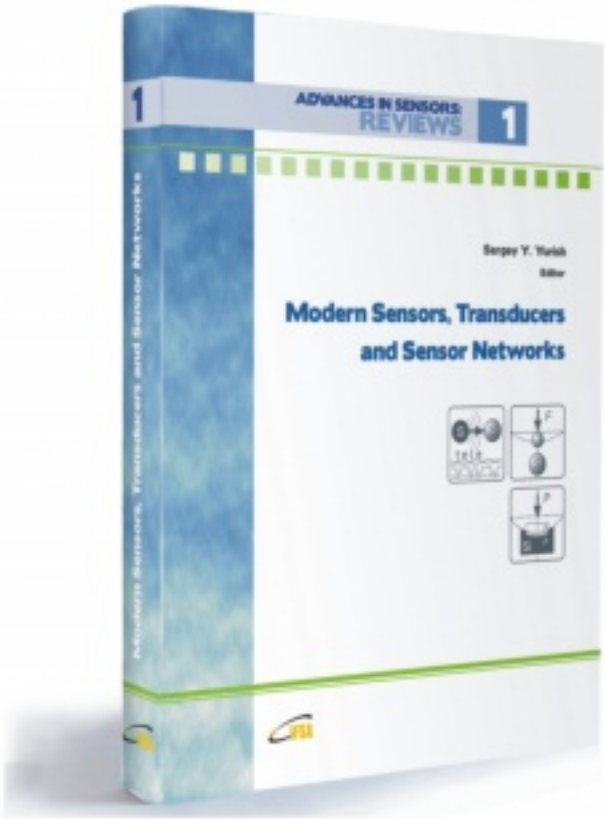
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