Sawtooth Fingered Comb Drive Actuator for Greater Displacement

Sang Wook Ha*, Sang-Woo Oh, Ju-Hee Hahm*, Kwon Hee Kim* and James Jungho Pak†**

Abstract - The electrostatic comb drive actuator is one of the main building blocks in the field of micro electro-mechanical systems (MEMS). Most of the comb actuators presented previously have fingers that are rectangular in shape which produce a stable, constant force output during actuation. The use of sawtooth fixed fingers in a comb drive, which were presumed to produce an increasing force output with displacement due to the increased number of regions where fringing force, the driving force of comb actuators, appear. The dimensions of the sawtooth were derived from finite element analysis (FEA) of simplified finger models with sawtooth type fingers of various dimension and were compared to the rectangular finger model that showed that the sawtooth type fingers have 7~9 times stronger driving force. Finally, comb drive actuators with sawtooth type and rectangular fingers were fabricated and although the gap was bigger, the comb actuator with sawtooth type fingers showed about 1.7 times greater electrostatic force than the one with rectangular fingers at equal driving voltages. In conclusion, using the proposed sawtooth type comb fingers in a comb drive makes it possible to increase its displacement or reduce the driving voltage.

Keywords: comb drive, actuator, fringing force, sawtooth finger, greater displacement

1. Introduction

Comb actuators are one of the most frequently used form of actuators in the field of micro electro-mechanical systems (MEMS). They are based on the working principle that an electrostatic force is generated between biased inter-digitated conductive comb fingers [1]. Due to their capability to generate force or vary capacitance they find a wide variety of applications in MEMS. Applications such as optical switch [2], micro-gripper [3], scanning probe device [4], radio frequency (RF) filter [5], resonators [6], and also use in driving elements such as vibromotors [7] and micro-mechanical gears [8] are some of the ways in which comb drive actuators are used. This diverse range of applications shows that small improvements of the comb drive actuator could have large effects on other MEMS devices.

There have been many researches where the comb drive actuator was re-designed to increase the electrostatic driving force which includes increased aspect ratio for the device [9], the introduction of sub-micron gaps between the comb fingers [10], and tailored finger shapes [11].

The objective of this paper is to explore a new sawtooth type finger design for increased driving force.

† Corresponding Author: Dept. of Electrical Engineering, Korea University, Korea. (pak@korea.ac.kr)
* Dept. of Electrical Engineering, Korea University, Korea.
** Dept. of Mechanical Engineering, Korea University, Korea. (kwonhkim@korea.ac.kr)
*** Korea Ocean Research & Development Institute, Korea. (swoh@kriso.re.kr)
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2. Electrostatic Comb Fingers

A comb drive actuator consists of moving and fixed conductive fingers. When bias voltages are applied to the fingers an electrostatic force is generated. This electrostatic force is the driving force of the comb drive actuator. The magnitude of the electrostatic force produced, together with the stiffness of the supporting beams then determines the displacement. The magnitude of the force depends on the applied voltage, the number of comb fingers used, the gap between the inter-digitated comb fingers, and the geometry of the fingers. Since the gap, which is the most important factor, is restrained by the fabrication process which makes it difficult to improve, the next important factor is the geometry of the fingers.

The most commonly used form of comb actuators are ones with rectangular inter-digitated comb fingers as shown in Fig. 1. When the length direction of the comb drive actuator is defined as the forward direction and the direction which is parallel to the substrate and perpendicular to the forward direction is defined as the side direction, in the case of a conventional rectangular fingered comb drive actuator, the driving force is constant in the forward direction regardless of the amount of area that the fingers are overlapped. The electrostatic force in the side direction appears in pairs that are equal in magnitude but opposite in direction and so cancel each other out.

In the case of the proposed sawtooth type comb finger as presented in Fig. 2, the driving force was presumed to increase in the forward direction as the engagement between the fingers increases. This is because the electrostatic force on the sides of the comb finger which also appears in pairs are equal in magnitude but not opposite in direction. So when the forces that appear on the sides are analyzed, it can be seen that the forces in the side direction cancel each other out but the forces in the forward direction are added. This explains the increase of the driving force with the increase in the engagement between the fingers.

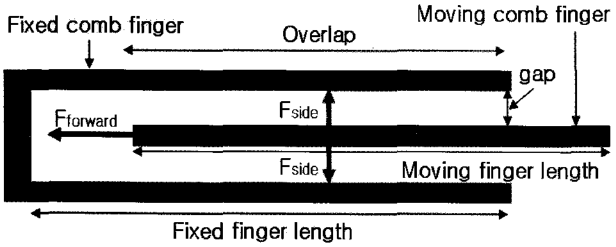


Fig. 1 A schematic diagram of a rectangular comb finger showing the electrostatic forces ($F_{forward}$: Force in the forward direction, F_{side}: Force in the side direction)

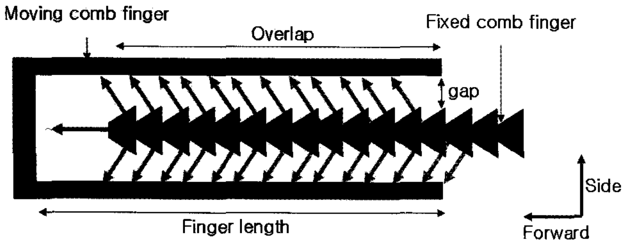


Fig. 2 A schematic diagram of a sawtooth comb finger showing the electrostatic forces

3. Sawtooth Dimension

The appropriate dimension of the sawtooth was derived through finite element analysis (FEA) using ANSYS. Simplified finger models with various dimensions were made. The number of teeth and the gap were set while varying only the width and the height of the tooth. The width was varied from 3 um to 6 um and the height was varied from 3 um to 5 um. A total of 25 models were created and simulated. Only the electrostatic force in the forward direction was considered when the applied potential was 100V. The results are shown in Fig. 3. The electrostatic force was less dependent on height as the width increased. As shown in the results, the model with the sawtooth dimension of 6 um in width and 4 um in height demonstrated the largest electrostatic force. This was chosen as the sawtooth dimension of the sawtooth type finger.

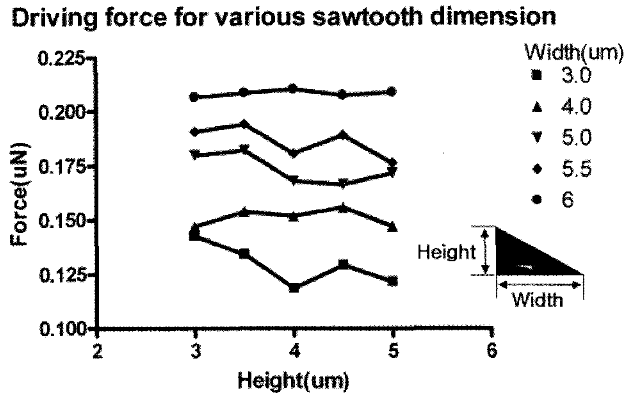


Fig. 3 A graph of the electrostatic force for various sawtooth dimensions

4. Design and Simulation

Four types of comb fingers were designed for comparison. The fingers were 160 um long with an overlap of 120 um. The gap which is defined as the shortest gap between the moving and fixed finger was set to 2 um. The height of the comb fingers were set to 20 um. The first of the fingers was the conventional rectangular finger as the reference for comparison and was named straight. The second was the sawtooth type with the sawtooth dimension derived from the simulations before and was named sawtooth1. The third model, which is similar to sawtooth1 but has a narrower width and increased number of teeth, was named sawtooth2. The fourth model named fishbone due to its resemblance, has the same derived dimension as sawtooth1 but was modified for the ease of fabrication as the pointed end of the sawtooth is hard to fabricate.

FEA simulations of the four models were done using ANSYS. The results of the simulation were visually plotted to show the electrostatic forces between the moving and the fixed fingers in each of the four finger models as presented in Fig. 4. In the case of the straight finger model the electrostatic forces are presented as it is commonly known. The forces are formed on the sides of the finger where the moving and the fixed fingers overlap and are equal in magnitude with the electrostatic force at the other side of the finger, which means they will be canceled out. The force is the largest at the corner of the finger commonly known as the fringing force and this is the main driving force of the comb drive actuator. In the case of sawtooth1, sawtooth2, and fishbone, strong electrostatic fringing forces appear at the sharp edges of the sawtooth. The strong fringing forces are not canceled but are added to form the driving force in the forward direction. This is in accord with the concept described earlier regarding the sawtooth finger.

FEA simulations were also done on the four finger models while varying the engagement of the moving finger and the fixed finger from 120 um to 150 um. The results are presented in Fig. 5. It is shown that the straight finger model has a constant force output regardless of the engagement while the others (sawtooth1, sawtooth2, and fishbone) show linearly increasing force output with the increase in engagement which is also as presumed before. The sawtooth type fingers indicated 7~9 times stronger driving forces compared to that of the straight finger model. Also in comparison by simulation with sawtooth type models proposed by others [11] the one proposed in this research showed about 6 times stronger electrostatic forces.

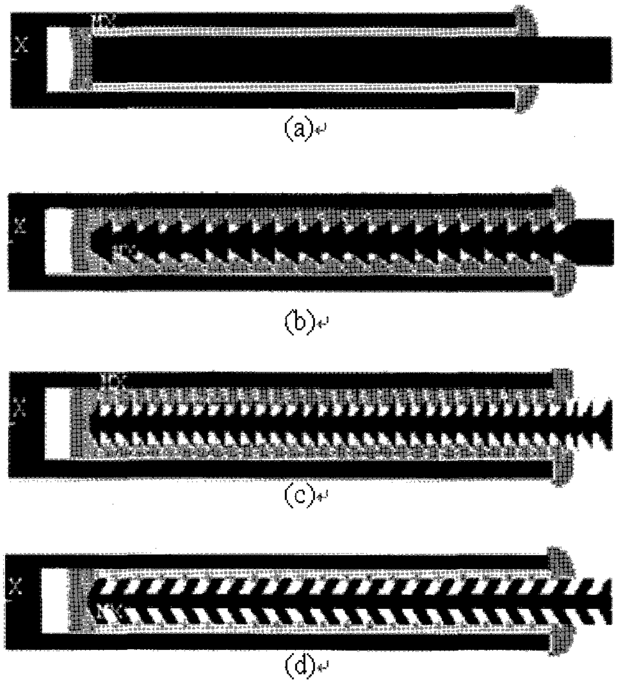


Fig. 4 FEA results of the various fingers showing the electrostatic forces; (a) Straight, (b) Sawtooth1, (c) Sawtooth2, (d) Fishbone

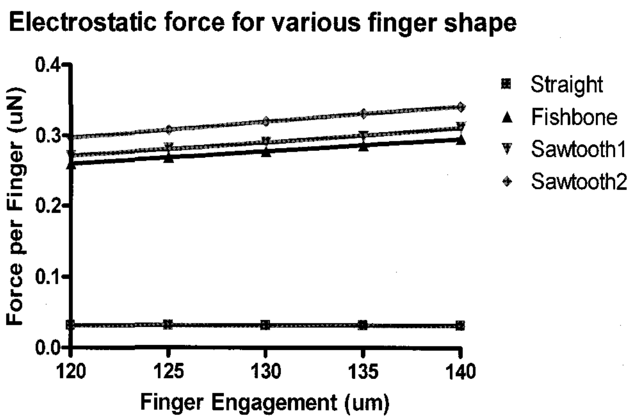


Fig. 5 Graph showing the force acting on a single finger for each of the sawtooth type fingers at various finger engagements

5. Fabrication

Comb drive actuators designed with straight, sawtooth1, and fishbone fingers were designed and fabricated by silicon surface micromachining technologies using a one mask fabrication process on a SOI wafer (20um/2um/500um) at the Inter-university Semiconductor Research Center in Seoul, Korea.

The fabrication process is illustrated in Fig. 6.

(a) Start from a P-type SOI wafer with crystal orientation of <100>.
(b) PR (AZ1512) was spin coated to the surface of the wafer.
(c) The PR was patterned through photo lithography and then developed.
(d) The active layer of the SOI wafer was etched by Deep Reactive Ion Etching (DRIE).
(e) The PR was ashed and stripped.
(f) The oxide was wet etched with HF (49%) releasing the moving part of the comb actuator. Paradichlorobenzene (p-DCB) was used to prevent stiction.

The results of the fabrication are shown in Fig. 7.

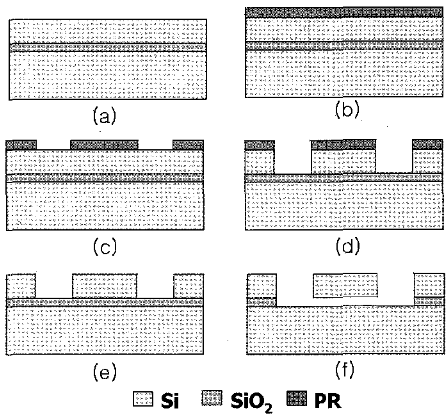
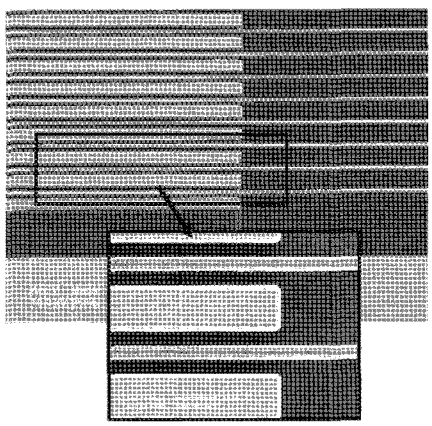
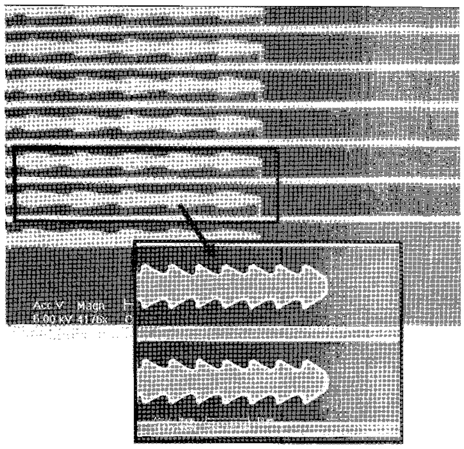


Fig. 6 Fabrication process using SOI wafer.



(a)



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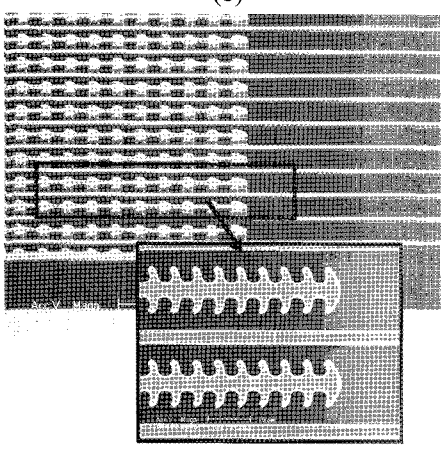

(c)

Fig. 7 SEM photograph of the fabricated comb drive actuators; (a) Straight, (b) Sawtooth1, (c) Fishbone

6. Measurement

In the experiments both the substrate and the moving part was connected to ground potential while the fixed parts were connected to both sinusoidal and DC bias voltages. The DC bias voltage was supplied using a power supply and the sinusoidal signal by a function generator.

The deflection was considered hard to measure by capacitance-to-voltage measurement using an impedance analyzer because the capacitance change is thought to be different for each finger type according to deflection. So an optical method was used. The comb drive actuators were driven at 100 Hz in order to make precise measurements without the use of expensive high speed cameras or stroboscopes. The measurement system was setup as shown in Fig. 8.

While the comb actuator was being driven, the movement of the moving finger was recorded by a CCD camera mounted on an optical microscope at 30 frames per second. Next each frame was extracted from the recorded video and filters were used to format the picture for the next process. Using National Instrument Vision Assistant, the edges at the end of the moving finger as well as the one facing it on the fixed finger part in each picture was recognized. The pixels between the edges were measured. The actual distance was derived by comparing the measured pixels to the measured pixels of a reference length that is known in the same picture. 5 of the longest distances were averaged and subtracted from an average of the 5 shortest distances to derive the deflection. This process was repeated while varying the amplitude of the sinusoidal signal from 0V to 5V.

This measurement was done for not only models with different fingers but for 3 models of comb actuators with identical fingers having different spring lengths. The deflection values derived for each of the models were divided by its elastic constant to obtain the driving force, which made it possible to compare with the forces derived from various models with different spring lengths.

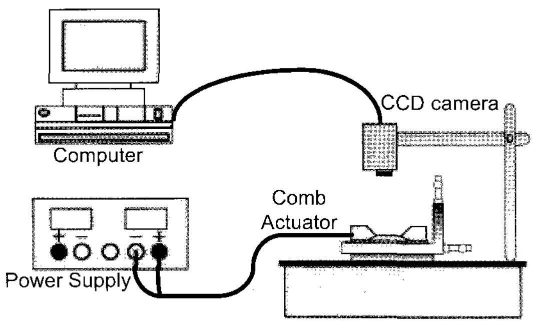

Fig. 8 A schematic diagram of the measurement system

7. Results

The results of the derived driving forces are shown in Fig. 9. The results suggest that the comb actuators with sawtooth finger generated about 1.7 times larger electrostatic driving force compared to the comb actuators with straight fingers.

Although the sawtooth fingered comb actuator showed bigger driving forces, it was not as big as simulated (7-9 times). The SEM photographs in Fig. 7 were analyzed and the gaps between the fingers were measured by the method similar to the one described above. The designed gap and measured gap are presented in Table 1. As indicated in the table, the gap between the fingers was far greater for sawtooth comb fingers than in the case of straight comb fingers. In the case of fishbone comb fingers the gap was slightly bigger. Also the top of the teeth was designed to be flat but the SEM photograph showed that it was more like a triangle. These differences between the designed device and fabricated device are deducted to have been the main cause for the decrease in driving force for the comb actuators with sawtooth fingers.

ANSYS simulation was performed for the sawtooth fingered comb actuator with the gap between the fingers set at 2.81 um. This was done to find out whether the bigger gap was the key reason for the decrease in driving force for the comb actuator with sawtooth fingers. The results are indicated in Fig. 10. The simulated electrostatic driving force of the sawtooth fingered comb actuator when the gap was 2.81 um was less then in the case in which the gap was 2um and similar to the measured electrostatic driving force. From these results it can be concluded that the decrease in driving force was due to the bigger gap of the sawtooth comb actuator.

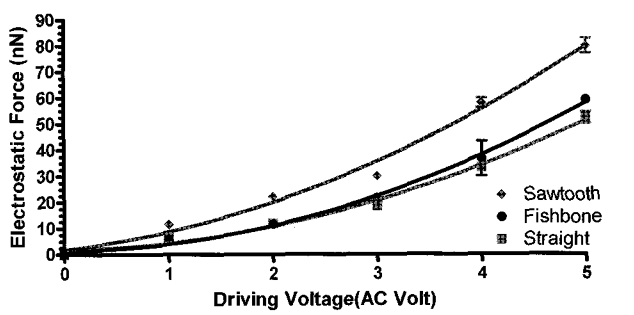

Fig. 9 Electrostatic driving forces of the comb drive actuators

Table 1 Gap between the fingers of each comb finger type

	Gap (um)		
	Straight	Fishbone	Sawtooth
Designed	2	2	2
Measured	2.32	2.47	2.81

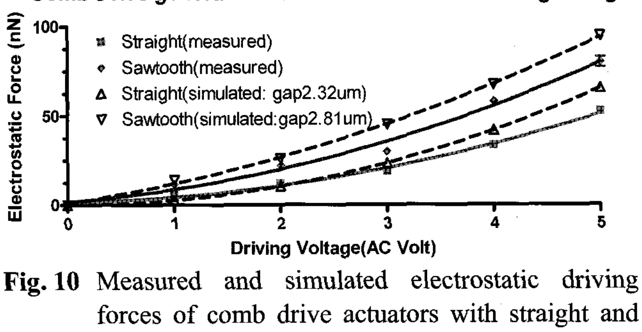

Fig. 10 Measured and simulated electrostatic driving forces of comb drive actuators with straight and sawtooth fingers

8. Conclusions

A sawtooth type comb finger that could produce larger electrostatic driving force than the conventional rectangular finger comb finger was proposed. The dimension of the sawtooth was derived by FEA simulations. Four simplified finger models were designed and compared through FEA simulations which showed that the sawtooth type finger models had 7~9 times stronger driving forces compared to rectangular finger models. Comb drive actuators with three types of fingers were designed and fabricated by silicon surface micromachining using a one mask fabrication process on a SOI wafer. The displacements were measured visually and although the gap was bigger the sawtooth type finger comb drive actuators showed about 1.7 times larger electrostatic force than the ones with straight fingers. Using the proposed sawtooth type comb fingers in a comb drive makes it possible to increase its displacement or reduce the driving voltage. This offers an attractive alternative to the conventional rectangular fingered comb drives when designing comb actuators for the use as an actuator as well as a sensor or a tunable capacitor in micro electro-mechanical systems with enhanced performance.

Acknowledgements

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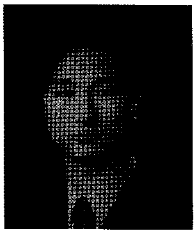
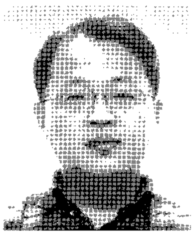


Sang Wook Ha

He received his B.S. degree in Electrical, Engineering from Korea University, Korea in 2004 and is working towards his M.S. degree in electrical engineering. His research interests are MEMS, LabVIEW and fuel cells.

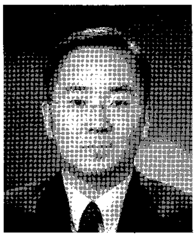
Sang-Woo Oh

He received his B.S. and M.S. degrees in Electrical Engineering from Korea University, Korea in 2002 and 2004, respectively. He currently works at the Korea Ocean Research & Development Institute, Korea. His research main interest is the control and communication systems in underwater.



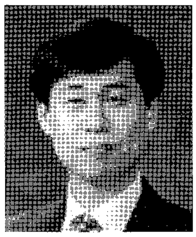
Ju-Hee Hahm

He received B.S. and M.S. degrees in Mechanical Engineering from Korea University, Korea in 1997 and 1999, respectively and is working towards his Ph.D. degree in Mechanical Engineering. His research interests are Plasticity and Design.



Kwon Hee Kim

He received his B.S. and M.S. degrees in mechanical engineering from Seoul National University, Korea in 1979 and 1981, respectively, and received his Ph.D. degree in Mechanical Engineering at MIT, USA, in 1987. He is currently a professor of mechanical engineering at Korea University. His research interests are in Engineering Design Creativity.



James Jungho Pak

He received his B. S., M. S. and Ph. D. degrees in Electrical Engineering from Purdue University, W. Lafayette, U.S.A in 1985, 1988 and 1992, respectively. He is currently a professor of electrical engineering at Korea University, Seoul, Korea. His research interests are semiconductor device/processing, OTFT, and micro/nano-systems including optical MEMS, bio-MEMS, micro drug delivery systems, and polymer based sensors and actuators.