Design of Novel Sequential Engagement Vertical Comb Electrodes for Analog Micromirror

Mingching Wu, Hung-Yi Lin, and Weileun Fang

***Abstract*—The vertical comb-drive actuator (VCA) is a promising component to drive analog as well as scanning micromirrors. This work demonstrates the concept of using "sequential engagement of vertical comb electrodes" to improve the linearity and to maximize the deflection for analog micromirror. This concept is achieved by varying the in-plane distribution of comb electrodes. The simulation and experiment results of vertical comb-drive actuator VCA with four different electrode-distribution designs demonstrated the feasibility of this study. In comparison, a modified (curved-profile) VCA was remarkably improved the performance of conventional (straight-profile) VCA. Experiments show that the curved-profile VCA improves the nonlinearity by 34% and increases the maximum angular motion for 2.3-fold.**

***Index Terms*—Analog micromirror, microelectromechanical systems, sequential engagement, vertical comb electrodes.**

I. Introduction

THE micromirror has successfully been exploited in various applications, such as projection display, data storages, and optical communications. The vertical comb actuator (VCA) is one of the most important actuators to drive micromirrors, especially for out-of-plane angular motion [1]. Because of its large displacement, process-compatible, and low power consumption, VCA has wide applications in microoptical systems, such as adaptive-optics [2], optical-switch [3], and laser display [4]. However, there are still two typical problems to replace the state-of-art design. First, an alignment problem between the upper and lower combs would induce a side-sticking phenomenon [5]. Side-sticking not only limits the maximum deflection of actuators but also results in unpredictable performance during structure design. Previous works have developed several self-aligned techniques to suppress the side-sticking problem, such as photoresist reflow [6], the self-assembly mechanism [7], and shadow mask with deep reactive ion etching methods [2], [8]. Second, the nonlinear behavior, which is due to the output force of VCA and varies quadratically with the driving voltage, is another problem. It is difficult to linearly control the position of VCA by varying the driving voltage and result in complex controller design.

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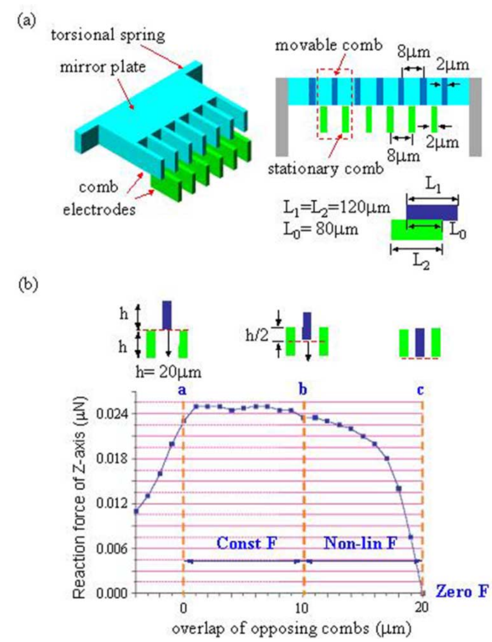

Fig. 1. (a) Typical microtorsional mirror driven by VCAs, and (b) electrostatic force in the out-of-plane direction as a function of the engagement of the vertical comb electrodes.

In general, the micromirror has resonant, digital, and analog operation modes. For the analog micromirror, the design of microactuator plays a key role in improving the performances of scanning angle, nonlinearity, and stability. To this end, a novel VCA for the application of analog micromirror has been designed and implemented in the present study. Much of the effort of previous works focused on suppressing the side-sticking phenomenon, especially in self-aligned VCA, but a lack of literature discusses how to improve the nonlinear behavior of VCA. This work is based on self-aligned VCA to propose the concept of "sequential engagement of comb electrodes" and attempts to vary the distribution of combs, so that the electrodes will engage sequentially [9]. Hence, the linearity and maximum deflection of the analog micromirror is significantly improved by the present VCAs. The details of "sequential engagement of comb electrodes" would be discussed and verified in this work.

II. Design and Simulation

Fig. 1(a) illustrates a typical micromirror consisting of a mirror plate and two torsional springs, and this torsional system is driven by vertical comb electrodes. In general, for the application of the scanning micromirror, the VCA is driven by

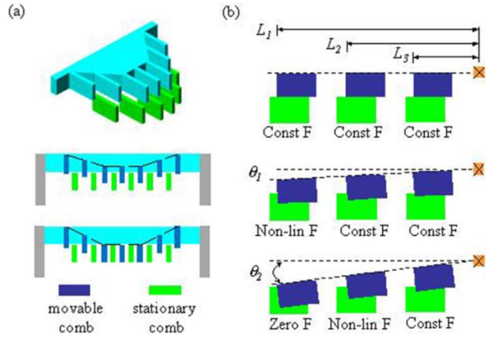

Fig. 2. (a) Schematic of distributed comb-drive actuator, and (b) sequential engagement of the electrodes at two different angular displacements.

an ac input at the resonant frequency of the torsional vibration system. For the application of the analog micromirror, the VCA is driven by a dc input, and the angular position of the mirror is tuned by the driving voltage. In each angular position, the electrostatic force provided by VCA is in equilibrium with the restoring force of torsional springs. The finite-element simulation results in Fig. 1(b) indicate the electrostatic force (in the engagement direction) induced by a pair of vertical comb electrodes (one moving and two stationary electrodes) varies with the engagement position of these electrodes [10]. In this case, the moving and stationary comb electrodes have the same thickness h, and the torsional spring has no deformation at position "a." Position "a" also represents the initial contact of the moving electrode and the stationary electrode. The electrostatic force in Fig. 1(b) is almost constant (Const F) between "a" and "b," where "b" is the position of half-thickness $h/2$ engagement of the electrodes. The force drops nonlinearly (Non-lin F) after position "b," and becomes zero (Zero F) when combs reach position "c" where the electrodes are fully engagement. On the other hand, the restoring force of torsional spring keeps increasing from "a" to "c." It is necessary to increase the driving voltage if the VCA moves exceeding "b," however, the lateral-instability problem may occur.

Fig. 2(a) illustrates a mirror which shows the proposed concept of "sequential engagement of vertical comb electrodes" by varying the in-plane distribution of combs. The distances L_i $(i = 1, 2, \ldots)$ between the rotating axis and the moving electrodes are not a constant. Fig. 2(b) illustrates the front and side views of electrodes during the engagement of two different angular positions. The moving electrodes have the same angular-displacement θ but different linear-displacement $L_i\theta$ in the out-of-plane direction. The combs farthest away from rotating axis have the largest out-of-plane linear displacement, and will move from the positions of Const F to Non-lin F (θ_1) and Zero F (θ_2) first. Meanwhile, the rest of the combs will sequentially reach the Non-linear F and Zero F regions after increasing the driving voltage. As a result, the variation of electrostatic force with the angular position for each moving electrode can be tuned by the distance L_i. In summary, the characteristic of driving voltage versus angular displacement for the VCA can be tuned by varying the distribution of the comb electrodes.

As shown in Fig. 3(a), this study employed four mirrors with different designs of electrode distribution, including straight (conventional design), hexagonal, tapered, and curved profiles, to demonstrate the present concept. The total number of comb electrodes and the stiffness of the torsional springs are the same

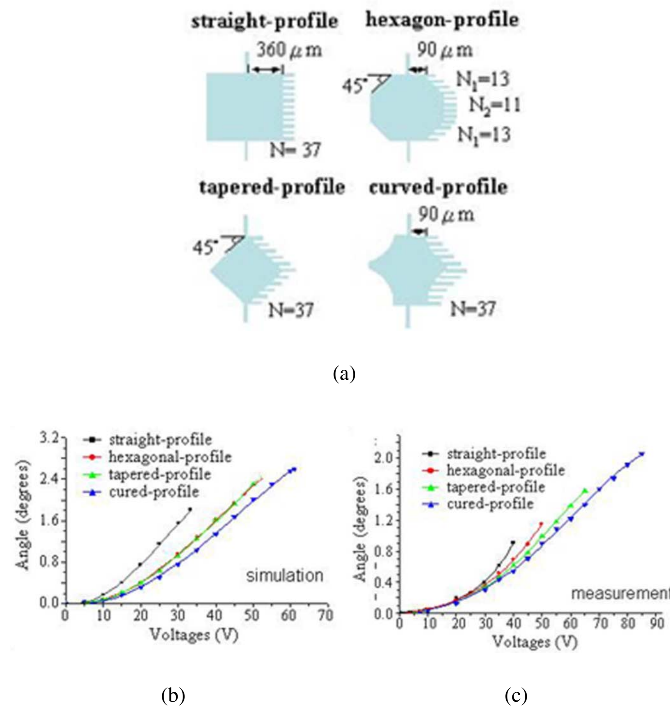

Fig. 3. (a) Micromirror with four different comb-profile designs, (b) predicted, and (c) measured angular displacements of the mirrors versus driving voltages for four different VCA distribution designs.

for these four mirrors. The commercial finite-element software was employed in this study to predict the characteristics of angular displacement varying with driving voltage. The typical results predicted by the finite-element method (FEM) for these four VCA designs are shown in Fig. 3(b). During the analysis, the maximum angular motion of the mirror was determined by the occurrence of the pull-in effect from electrodes.

The rotation angle can be increased after decreasing the distance between the rotational axis (torsion bar) and the moving comb pairs. However, higher actuation voltage (i.e., electrostatic force) is required. Thus, the in-plane electrostatic force (orthogonal to the driving direction) resulted from comb electrodes is also increased. This may lead to the lateral instability of VCA and limit the real rotation angle. As to the present VCAs, the in-plane electrostatic force is reduced by the design of sequential-engagement comb electrodes. Thus, the larger maximum angular motion is increased by increasing driving voltages. In the present cases, the mirrors with conventional straight-profile and curved-profile VCAs have a maximum angular motion of 1.8° and 2.6°, respectively. Thus, the maximum angular motion has been improved by 45%. Moreover, the nonlinearity has also been improved by 15% (i.e., decreased from 23% for the straight-profile VCA to 19.6% for the curved-profile VCA). The nonlinearity is defined as the maximum deviation of the measured curve from a straight line between zero and maximum angle [11].

III. Experiment and Results

In applications, this study applied the Molded Surface-Micromachining and Bulk Etching Release II (MOSBE II) process [12] to successfully implement the mirrors of different VCA designs in Fig. 3(a). Fig. 4 shows

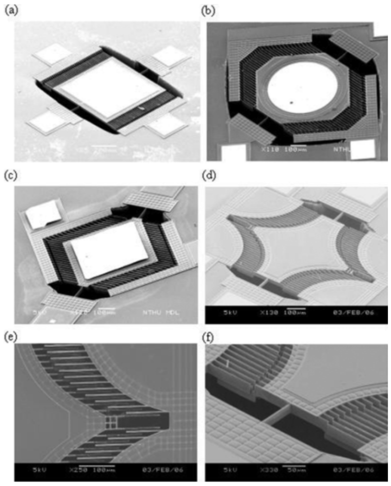

Fig. 4. SEM micrographs of (a)–(d) fabrication results of the presented four different VCA designs, (e) zoom-in of the self-aligned VCA, and (f) high-aspect-ratio torsional spring.

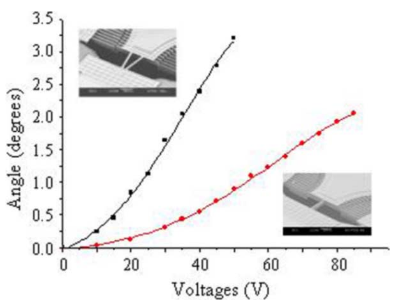

Fig. 5. Linearity of angular motion versus driving voltage can be further improved by means of spring design.

the scanning electron microscope (SEM) photos of typical fabrication results. The zoom-in photo in Fig. 4(e) shows the comb electrodes of the fabricated VCA are self-aligned after the process. Moreover, the high-aspect-ratio spring was also available using the MOSBE II process, as indicated in Fig. 4(f). Thus, the unexpected side-sticking was prevented by the self-aligned VCA, and unwanted bending was reduced by the stiffness of high-aspect-ratio spring during test.

Various tests have been conducted to demonstrate the presented concept. The commercial optical interferometer was used to characterize the angular displacements of the mirror at different driving dc voltages, as shown in Fig. 3(c). The results predicted by the FEM analysis in Fig. 3(b) agree well with the measurements in Fig. 3(c). The end point of each curve shows the conditions of maximum angular displacement and maximum driving voltage right before side-sticking occurred. For conventional straight-profile VCA, its maximum angular motion is 0.91° and the nonlinearity of angular displacement versus driving voltage is 29.4%. For curved-profile VCA, its maximum angular motion is 2.06° and the nonlinearity of angular displacement versus driving voltage is 21.9%. Thus, the curved-profile VCA improves the nonlinearity by 34% and increases the maximum angular motion for 2.3-fold. Moreover, according to the "sequential engagement of electrodes," the nonlinearity of the curved-profile VCA even dropped to only 2.2% when operating at an angular motion of less than 0.4°.

IV. Conclusion

This work successfully improves the linearity and maximum deflection of analog micromirror using the concept of sequential-engagement comb electrodes. By varying the in-plane distribution of comb fingers, the engagement of electrodes can be easily tuned. This study has investigated four micromirrors with different in-plane distributions of comb electrode. In applications, the MOSBE II process was employed to implement these four micromirrors. The simulation and experiment results of these four analog mirrors demonstrated the feasibility of the present concept. However, the distribution profile of comb electrode has not yet been optimized. It is possible to further improve the linearity as well as maximum deflection of analog micromirror by tuning the length of comb finger. The maximum angular motion and nonlinearity of micromirror driven by VCAs can be further improved by the curved-profile electrodes together with V-shape spring, as shown in Fig. 5. The measurement results in Fig. 5 show the maximum angular motion of the mirror with V-shape spring becomes 3.21°, and the nonlinearity of deflection versus driving voltage becomes 14.8%. As compared with the mirror with conventional VCA in Fig. 3(c), the mirror with curved-profile VCA and V-shape thin spring has improved the nonlinearity of 50%, and increased the maximum angular motion of 3.5-fold.

References

[1] D. Hah, S. T. Y. Huang, J. C. Tsai, H. Toshiyoshi, and M. C. Wu, "Low-voltage, large-scan angle MEMS analog micromirror arrays with hidden vertical comb-drive actuators," *J. Microelectromech. Syst.*, vol. 13, pp. 279–289, Apr. 2004.

[2] D. Lee, U. Krishnamoorthy, K. Yu, and O. Solgaard, "Single-crystalline silicon micromirrors actuated by self-aligned vertical electrostatic combdrives with piston-motion and rotation capability," *Sens. Actuators*, vol. 114, pp. 423–428, 2004.

[3] J. C. Tsai and M. C. Wu, "A high port-count wavelength-selective switch using a large scan-angle, high fill-factor, two axis MEMS scanner array," *IEEE Photon. Technol. Lett.*, vol. 18, no. 13, pp. 1439–1442, Jul. 1, 2006.

[4] R. A. Conant, J. T. Nee, K. Lau, and R. S. Mueller, "A flat high-frequency scanning micromirror," in *Proc. Solid-State Sensors Actuators Workshop*, Hilton Head, SC, Jun. 2000, pp. 6–9.

[5] O. Tsuboi, Y. Mizuno, N. Koma, H. Soneda, H. Okuda, S. Ueda, I. Sawaki, and F. Yamagishi, "A rotational comb-driven micromirror with a large deflection angle and low drive voltage category: Micro-optical devices and systems," in *IEEE MEMS'02*, Las Vegas, NV, Jan. 20–24, 2002, pp. 532–535.

[6] P. R. Patterson, D. Hah, H. Nguyen, H. Toshiyoshi, R.-M. Chao, and M. C. Wu, "A scanning micromirror with angular comb drive actuation," in *IEEE MEMS'02*, Las Vegas, NV, Jan. 20–24, 2002, pp. 544–547.

[7] K. Isamoto, T. Makino, A. Moroswa, C. Chong, H. Fujita, and H. Toshiyoshi, "Self-assembly technique for MEMS vertical comb electrostatic actuator," *IEICE Electron. Express*, vol. 2, pp. 311–315, 2005.

[8] S. Kwon, V. Milanovic, and L. P. Lee, "Vertical combdrive based 2-D gimbaled micromirrors with large static rotation by backside island isolation," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 3, pp. 498–504, May/Jun. 2004.

[9] M. Wu, H.-Y. Lin, R. Chen, and W. Fang, "A novel sequential engagement electrodes for vertical comb-drive actuator," in *IEEE MEMS'07*, Kobe, Japan, Jan. 21–25, 2007, pp. 655–658.

[10] J. M.-L. Tsai, H.-Y. Chu, J. Hsieh, and W. Fang, "The BELST II process for a silicon high-aspect-ratio micromaching vertical comb actuator and its applications," *J. Micromech. Microeng.*, vol. 14, pp. 235–241, 2004.

[11] G. T. A. Kovacs, *Micromachined Transducers Source Book*. New York: McGraw-Hill, 1998, ch. 1.

[12] M. Wu and W. Fang, "Design and fabrication of MEMS devices using the integration of mumps, trench-refilled molding, DRIE and bulk silicon etching processes," *J. Micromech. Microeng.*, vol. 15, no. 3, pp. 535–542, Mar. 1, 2005.