Oscillatory motion driven elastic fins MEMS liner micromotor in 2-step DRIE process

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INTRODUCTION

This paper is the development of the initial idea presented in *"high-torque micro-motor for MEMS and MOEMS applications."*[1] The linear micro-motor consists of a beam with elastic fins and linear actuators such as electrostatic comb-drives located on both sides along the rail the beam travels. The micro-motor is powered by the mechanical rectification of oscillatory motion of the actuators.

The design and the fabrication of the test structures will be discussed. The principle of operation of each test structure is then briefly discussed. The calculations and the analysis of the test structures will be given to verify the performance and the expected results of the test structures and the overall system. Finally, the applications of our liner micromotor will be presented.

DESIGN/FABRICATION

MUMPS is a three-layer polysilicon surface-micromachining process. It is chosen for prototyping the design, not for the final product runs. The advantages of using a prototyping foundry are the extremely low cost and reasonable turn-around time. The low cost and frequently scheduled fabrication runs of many commercial foundry processes reduced the scheduling and financial risk. Hence, the designer is free to try many variations, which encourages creativity. One disadvantage of MUMPS is that the operational characteristics of many MEMS devices are process dependent, so the test structures may have to be readjusted for the final production process. [2]

The MUMPS process of the finned beam starts with a thick CVD oxide growth on top of the substrate. The oxide layer is patterned with anisotropic reactive ion etching (RIE) to give openings for the fins. The fins are then deposited with low-pressure chemical vapor deposition (LPCVD). Consequent Chemical Mechanical Planarization (CMP) is performed to enhance the adhesion of the fins to the beam. Then, a blanket layer of polysilicon (for the beam structure) is deposited and patterned; and another layer of thick CVD oxide is grown and patterned with RIE for fin openings. Finally, the fins are deposited (LPCVD) and planarized (CMP). After the sacrificial oxide etch, the test structure is released and the fins are free to move. One drawback of this MUMPS process is that the material chosen for the fins must be able to withstand the high temperature (>600°C) CVD process. In addition, the symmetry for the fins on both sides of the structure is hard to achieve.

An alternative and better approach is by 2-step DRIE of SOI structure. The first step of DRIE (dry SF_6O_2 plasma etch) is done to define the high-aspect-ratio fin openings on both sides as shown in Fig.1. Then the fin material is deposited with LPCVD, and followed by CMP to planarize and remove unwanted fin layer on top of the substrate. Then second DRIE step is performed to release the fins. If poly silicon is used as fin material, an additional lithography step is needed to protect poly silicon fins while second DRIE step is being performed. Finally, isotropic oxide etch is performed to release the whole test structure.

TEST STRUCTURES

The linear micro-motor consists of a slider (a beam with elastic fins) and linear actuators such as electrostatic comb-drives located on the side along the rail the slider travels. The micro-motor is powered by the mechanical rectification of oscillatory motion of the actuators.

When the actuators engage with the fins, the force applied by the actuators cause the fins to bend; and this bending of the fins in turn put motion into the stationary slider. The normal forces exerted on the opposite sides of the fins canceled each other but the axial forces along the slider cause the linear motion of the slider, and the direction of the movement depends upon which pairs of actuators being resonated. When the actuators are disengaged, the fins are allowed to get back into their original positions. Once disengaged, the stiction force between the slider and the substrate tend to prevent movement.

Continuous directional motion of the micro-motor can be achieved by matching the oscillations of the actuators and the movement of the slider. The motion of the micro-motor depends on the type of actuators used (therefore the force and the oscillatory motion of the actuators), the length and the elastic property of the fins, the tilt angle of the fins with respect to the beam, and the number of fins.

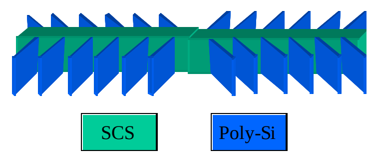

Fig. 1. Slider and its finned structure

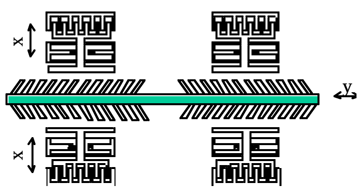

Fig. 2. Linear micro-motor system components

As illustrates in Fig. 2, the system consists of a linear slider (a beam with elastic fins) located between two pairs of electrostatic comb-drive actuators, which can exert forward and backward vibratory forces on the slider, depending on which pair of the actuators is resonated.

Fig. 3. illustrates two-step operation of the linear micro-motor. First, the forward-drive pair of comb-drive is resonated, causing the force exerted on the forward fins, and this in turn puts forward motion into the slider. Next, the backward-drive pair of comb-drive is resonated. The force exerted on the

backward fins causes the backward motion of the slider.

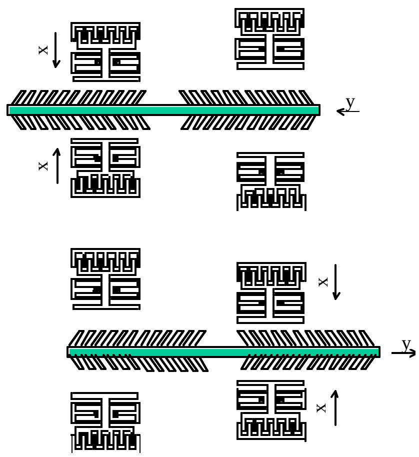

Fig. 3. Two-step operation of the linear micro-motor

Many types of actuation have been used in MEMS designs. The choices include magnetic, thermal, piezoelectric, and electrostatic actuators. Although each has its particular attributes, an electrostatic actuator has the advantage of faster response over its thermal counterpart, and also unlike magnetic actuators, electrostatic actuators do not need external sources.

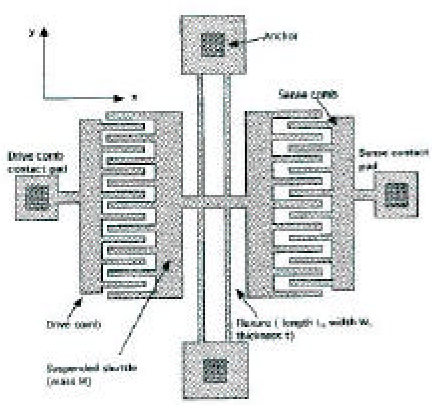

Fig. 4. Electrostatic comb-drives

EXPECTED RESULTS

The dynamic behavior of the whole system is quite complex. For example, calculation of the energy transfer between two resonating comb-drives on opposite sides is not trivial. However, a simplified model can predict the behavior of the system. The simplified analysis is broken down into two parts. It begins with analytical descriptions of the comb-drive actuators and followed by the motion and displacement of the slider when its fins and the comb-drives engage.

The force in the x-direction out of the comb-drives is constant and can be written as:

$$F_x := \frac{1}{2} \cdot \left(\frac{d}{dx} C\right) \cdot V^2 \qquad [1]$$

where V is the applied voltage and

$$C := 2 \cdot \varepsilon_0 \cdot \frac{t \cdot x}{g} \qquad [2]$$

is the overlap capacitance on both sides of a finger and x here is the overlap length of two fingers. If the applied voltage is sinusoidal with varying amplitude,

$$V(t) := V_{dc} + v_{ac} \cdot \sin(\omega \cdot t), \qquad [3]$$

$$F_x := \frac{1}{2} \cdot \left(\frac{d}{dx} C\right) \cdot \left(V_{dc}^2 + V_{dc} \cdot v_{ac} \cdot \sin(\omega \cdot t) - \frac{v_{ac}^2}{2} \cdot \cos(2 \cdot \omega \cdot t) + \frac{v_{ac}^2}{2}\right) \qquad [4]$$

The comb-drive also satisfies the standard driven damped system equation

$$f_{ext}(t) := M \cdot \frac{d^2}{dt^2} x(t) + b \cdot \frac{d}{dt} x(t) + k_x \cdot x(t) \qquad [5]$$

where

M = total mass of the comb structure,
b = couette damping coefficient,
k_x= spring constant of the folded beam.

The steady state solution is then

$$x_{ss}(t) := X_{dc} + X_\omega \cdot \sin(\omega \cdot t - \phi_1) - X_{2\omega} \cdot \cos(2 \cdot \omega \cdot t - \phi_2) \quad [6]$$

where

$$X_{dc} := \frac{1}{2 \cdot k_x} \cdot \left(\frac{d}{dx} C\right) \cdot \left(V_{dc}^2 + \frac{v_{ac}^2}{2}\right) \quad [7]$$

$$X_\omega := \left(\frac{d}{dx} C\right) \cdot V_{dc} \cdot v_{ac} \cdot \frac{1}{\sqrt{\left(k_x - M \cdot \omega^2\right)^2 + b^2 \cdot \omega^2}} \quad [8]$$

$$X_{2\omega} := \left(\frac{d}{dx} C\right) \cdot v_{ac}^2 \cdot \frac{1}{4\sqrt{\left(k_x - M \cdot \omega^2\right)^2 + 4 \cdot b^2 \cdot \omega^2}} \quad [9]$$

$$\phi_1 := \mathrm{atan}\left(\frac{b \cdot \omega}{k_x - M \cdot \omega^2}\right) \quad [10]$$

$$\phi_2 := \mathrm{atan}\left(\frac{2 \cdot b \cdot \omega}{k_x - 4 \cdot M \cdot \omega^2}\right) \quad [11]$$

And the transient solution can be found as follow:

$$x_{tr}(t) := \exp(\alpha \cdot t) \cdot (A \cdot \cos(\beta \cdot t) + B \cdot \sin(\beta \cdot t)) \quad [12]$$

where A and B are some constants and

$$\alpha := \frac{-b}{2 \cdot M} \qquad \beta := \sqrt{\frac{k_x}{M} - \alpha^2} \quad [13]$$

The total solution is just

$$x(t) = x_{ss}(t) + x_{tr}(t) \quad [14]$$

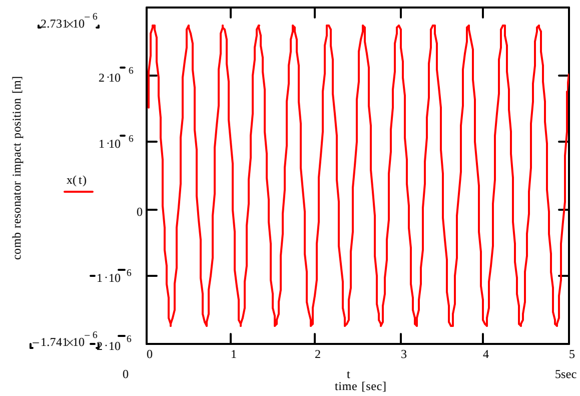

Fig. 5. simulation plot of displacement vs. time at resonant frequency w_n = 7.4kHz with t=L=g=2mm, N_g=50, V_{dc}=50V, v_{ac}=12V.

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Layout

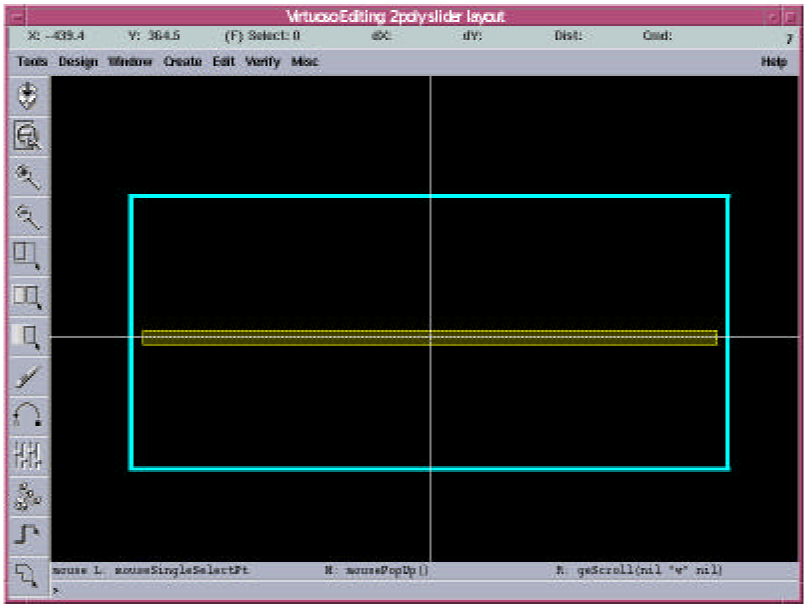

Fig. 1 Slider

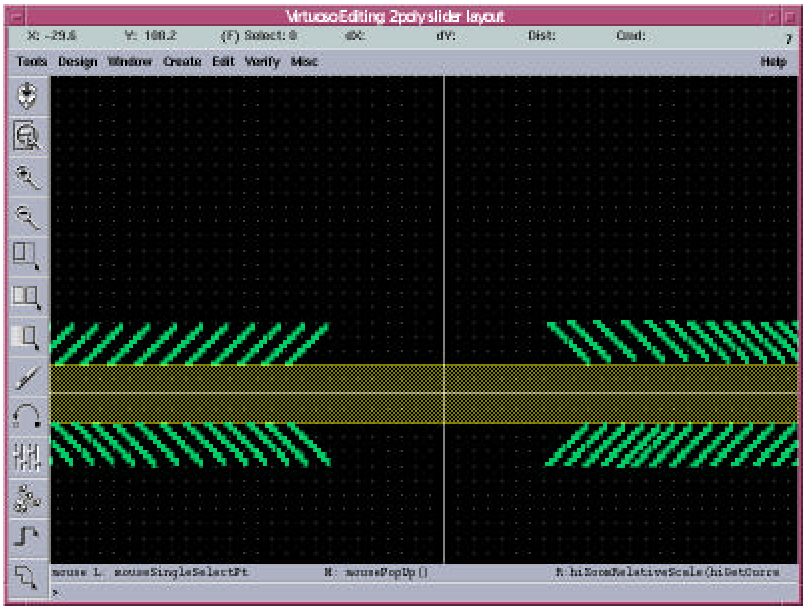

Fig. 2 Slider Zoom-in

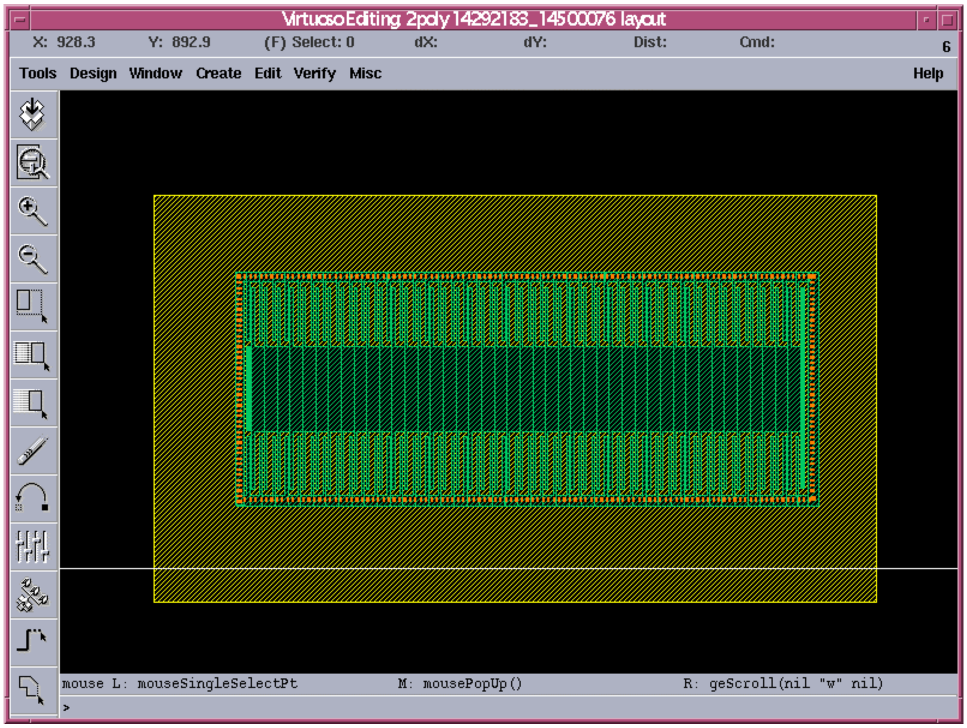

Fig. 3 electrostatic comb-drive