Microelectomechanical Lift-up Mechanism Using a 'Saw Tooth Drive' Driven by Electrostatic Actuator - The World's Smallest Book

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INTRODUCTION

R.P. Feynman's lecture script 'There's Plenty of Room at the Bottom' [1] starts with thinking of writing down the Encyclopedia of Britannica on the head of a pin. Inspired by this article, we considered a challenge on making the smallest book in the world by MEMS technology.

Current records of the smallest book in the world have some variety in it, but all of them was achieved by just making small book made of paper, and their size is more than 5mm x 5mm at least [2][3].

In this project, we tried to design a book smaller than 1mm x 1mm made of polysilicon using MEMS processes. However, to turn over the page of this book without needle or probe, there must be a certain mechanism to lift up the page. And it is the most difficult part in the design of the 'World's smallest book'

There have some researches to achieve automatic lift-up mechanism, but most of them were not fully automatic method to lift up [4]. Hence, we tried to design a simple lift-up mechanism that can be driven by electrostatic actuators only.

In this paper, we will describe our idea and design about the 'saw tooth drive' that will convert a horizontal movement into a rotation and how it can be applied to the mechanism of turning over a page.

DESIGN

I. Concept

Figure 1 shows the basic concept of our idea about the 'saw tooth drive' that converts horizontal movement into rotation of 180 degree. A long spindle that has cross section of square is placed on a driving gear that moves perpendicular to the spindle axis. And make the hinges that are located at both ends of the spindle should clamp the spindle so that it cannot move horizontally. But the spindle can rotate freely and also can move a little bit upward or downward. Right near the spindle, there is a saw tooth on the driving gear, which have two V-shaped trenches and a small flat on the topside between the trenches. The length of this flat is smaller than a side of the cross section of the square spindle.

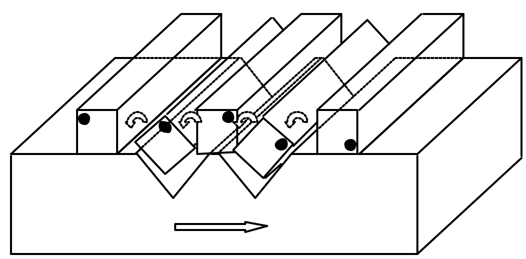

Fig.1 The basic concept of converting Horizontal movement into rotation

If the driving gear starts to move horizontally, the square spindle will fall into the trench of the saw tooth and start to rotate about 45 degree when it slides into the trench. And after it has passed the center of the trench, the other side of the square spindle would slide up the adjacent sidewall as the saw tooth keep on moving. As the spindle slides up the hill, its center of mass will move out of the point of contact on the sidewall, and the floated side will fall down on the topside of the tooth. This makes the spindle rotated 90 degree to the initial status. After a little more slide with this status, the center of mass will be moved out of the tooth topside and the spindle will rotate again when it falls into the next trench. Finally, after climbing up from this trench, the spindle will accomplish the 180-degree rotation. This rotation can be repeated with two more saw tooth added, if we want to rotate 360-degree.

In this project, we would use this '2-trench saw tooth drive' in rotating a spindle with some levers attached in the middle of it, and the levers will be inserted underneath the page of the book. By rotating the spindle, these levers will lift the plate (page) up and turn over the page. And for the horizontal movement of the driving gear, we can use typical comb drive [5][6] with serpentine spring structure attached on the moving side.

II. Fabrication Method

To make a V-shaped trench, we will use the anisotropic wet etch solutions of the single crystal silicon, such as KOH, EDP or TMAH. These wet etch solutions shows dramatically different etch rates to the <100> direction and to <111> direction [7]. Therefore, with the proper size of two rectangular opening of the mask separated properly, we can make two adjacent V-shaped Trenches on the silicon surface. To use above process in making the trenches for saw tooth, the first layer of our structure (the saw tooth drive and its actuators) should be fabricated with the single crystal silicon, which is to be patterned by DRIE process on a SOI wafers For this DRIE etch, this mask for the saw tooth drive body must be aligned on these V-shaped grooves, and also the top width of the saw tooth should be adjusted relatively shorter than the length of the V-shaped grooves so that the sloped triangular surfaces on both sides can be etched away.

After these two steps, rest of the structures can be fabricated by poly silicon layers. There are at least 3 layers of poly silicon required for the spindle with lever, the page of the book, and the hinges for the page. And also, the sacrificial SiO_2 layers between the poly layers should be planarized by CMP to make the page of the book flat. For this reason, we propose to fabricate these structures using the Sandia National Laboratories' SUMMiT V™ technology.

III. Mechanics of Operation

To complete a 180-degree rotation of the spindle, the saw tooth drive should move horizontally at least twice the width of the V-shaped groove. After moving this distance, the spring attached to the comb drive should stop the system. This can be achieved by the equilibrium of forces of comb drive and spring.

$$F_c = N_g \frac{1}{2} eV^2 \frac{t}{g} = k \cdot \Delta x = F_s$$

F_c: Comb drive force
F_s: Spring force
N_g: Number of gaps in comb drive
t: thickness of the SOI silicon layer
g: gap width between the combs
k: Spring constant
Dx: displacement needed

In above equation, *t* and *g* is determined by SOI thickness and design rule. Once spring constant k and *Dx* is decided, the number of gaps (N_g) can be optimized to minimum.

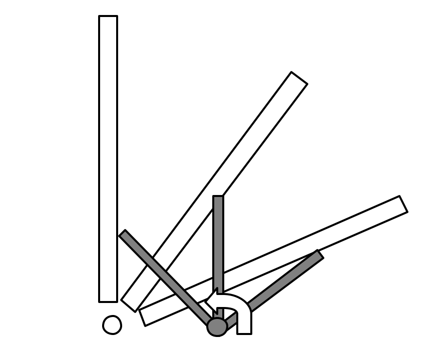

Fig.2 The minimum spindle rotation required to turn over the page

One other thing to be considered in design of this structure is that the torque of the spindle should make a torque enough to lift up the big page plate. Required condition for the design can be decided by comparing the angular moments of the spindle and the page plate. The minimum angle that the spindle with the lever must rotate to make the page plate turn over 90 degree ($\pi/2$) is 270 degree

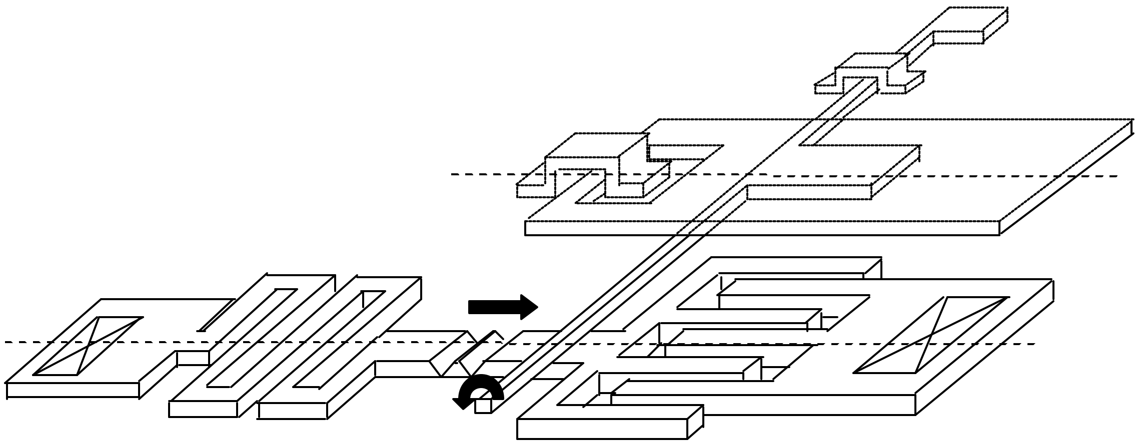

Fig.3 The schematic sketch of the page lift-up system using saw tooth drive

(3π/2) as shown in Fig.2. Therefore, the angular momentum of the spindle to rotate 3π/2 must bigger than that of the page plate. Suppose that the length of a side of the square spindle is *a*, the length of the spindle is *L*, the thickness of the page plate is *b*, and the length of a side of square-shaped page is *c*. If we ignore the loss of energy due to the friction, we can write these equations.

$$I_s \cong \frac{1}{6} r \cdot a^4 L$$

$$I_p = \frac{1}{12} r \cdot bc^2 (b^2 + 4c^2)$$

$$I_s \cdot \frac{3}{2} p > I_p \cdot \frac{p}{2}$$

$$\Rightarrow a^4 L > \frac{1}{6} bc^2 (b^2 + 4c^2)$$

I_s: Moment of Inertia for a square spindle
I_p: Moment of Inertia for a square spindle
r : Density of the poly silicon

In the definition of I_s, we have ignored the portion of the levers, assuming that *L* is sufficiently long enough compared to the width of the levers. For the thickness *a* and *b* can be determined in the standard process such as SUMMiT V™, we should design the *L* and *c* should meet above requirement.

TEST STRUCTURES

Fig.3 shows the schematic sketch of our page lift-up system. A poly silicon spindle with lever is sitting on the saw tooth drive fabricated by DRIE process. Applying the voltage difference between the fixed end of comb drive and the fixed end of spring will move the saw tooth drive to the right, and make the square spindle rotate counter-clockwise. This rotation will lift the lever up and turn the page hinged on one side. And Fig.4 shows the cross section of these structures along two dashed lines on the Fig.3. POLY0 and OX1 layers are the initial silicon and insulator layers of the SOI wafer.

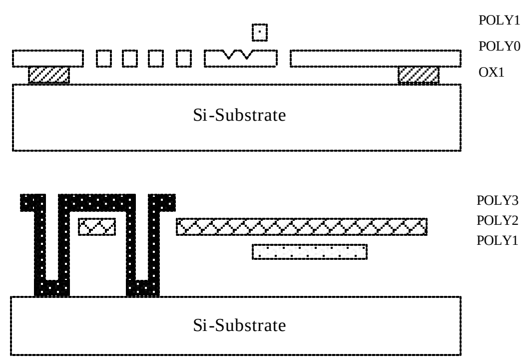

Fig.4 Cross sections of the structures along the dashed lines on the Fig.3

As the test to find out the real threshold of our fully working smallest book structures, we propose to fabricate several test components which has the design shown in Fig.3 and Fig 4 with different values of *L* (the length of the spindle) and different values of *c* (the dimension of the page plate). The result from this split test will give us the practical ranges of the dimensions of this lift up mechanism.

EXPECTED RESULT

Using the equation that describes the requirements on angular moments, we can predict the minimum *L* as multiples of *c*. In SUMMiT V™ process, *a* is 1µm (thickness of POLY1 layer) and b is 1.5µm (thickness of POLY2 layer). The results are shown in Table 1 below.

Table 1 Predicted minimum of L on various choices of c

c (Dimension of the page)	L_{min} (Minimum length of the spindle)
5µm	639µm
6µm	1316µm
7µm	2428µm
10µm	10mm

This values look somewhat disappointing for it is required to use a 2mm-long spindle to lift up the 7µm x 7µm page. However, if we can use custom fabrication process where POLY1 can be thicker than POLY2, or if we can substitute POLY1 with other material whose density is higher than poly silicon, we will be able to reduce the length of spindle.

CONCLUSION

In this paper we have suggested a concept of a 'saw tooth drive' that converts a horizontal movement into a rotation and its application to the lift up mechanism. If this mechanism may work, it would be applied to the various lift up applications.

Unfortunately, we may not be able to make an effective saw tooth drive with current standard process. Maybe that's why still everybody needs probes to lift up the MEMS structures. But during this project, we learned that development of automatic lift-up mechanism can be one of the interesting and great research themes of MEMS.

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