Design of a g-force meter on Si wafer, based on motor driven by photons

J. Valenzuela, S. Mil'shtein
Advanced Electronic Technology Center
ECE Department, University of Massachusetts-Lowell, USA

ABSTRACT

We report the design of a micro-motor driven by light that could be used as a g-force meter or navigation instrument in space applications. The new design, based on a scale of micro-machines fabrication, takes into consideration the concept of radiation pressure as a method of actuation. The materials selected reduce friction and increase reflectivity of the structure, allowing a better conversion of the radiant energy into movement.

Keywords: mems, motor, drie, liga, radiation pressure.

1 INTRODUCTION

The photon, being a particle with zero rest mass, was described early on the last century as the responsible for the mechanical pressure produced by light. Travelling at the speed of light, its momentum is directly proportional to its frequency as showed by Compton in 1922 [1]. In this sense, how much of that momentum can we transform in mechanical movement? It all depends on the material that those photons will impact and at what angle this interaction takes place. As shown in Equation (1), the reflectivity of the material plays a main role in the amount of momentum that can be transferred to any object in form of pressure [2]. This parameter also depends on the frequency, providing certain limitations on effectiveness when choosing materials.

$$RP - \frac{2 \cdot R \cdot I}{c} \qquad (1)$$

Where **R:** Reflectivity index (1 – total reflection, 0 – total transparency)
I: Light intensity
c: Speed of light

2 MEMS OPTICAL MOTORS

One of the biggest limitations of the widespread use of rotating or moving MEMs is the wear and tear produced by interaction or friction during operation [3-4]. Due to the dimensions involved, this is particularly important not only in mechanical terms but also in electrostatic too. The possibility of having a structure that increases its electrostatic charge due to its movement at micro meter level, not only can be structurally devastating when in contact with other components, but can also modify the desired response of the whole unit.

Few attempts of mechanical design of light driven MEMs motors have been reported in the literature [5]. The amount of torque that can be obtained in any structure of these dimensions is so low that gives to conventional design ideas a very bad start point. For example, a simple laser with an intensity of $5x10^6$ [W/m^2] can produce a torque on a micrometer level of approximately 10^{-18} [N-m], which doesn't take into account a friction component that will lower even more the expectance of any movement. With regular Silicon structures, this means practically no movement at all, making this kind of configuration not suitable for any kind of conventional application.

In recent years, new designs and use of new materials have opened the field to fresh ideas, including spacecrafts driven by light [6]. In the area of MEMs, the use of light as an actuation method has been limited to optical tweezers for the most part, having a reduced number of examples on implementation of MEMs driven directly by light.

In this sense, an optical micro motor can be a very useful tool in non-tripulated spacecraft, serving as a guidance system to find orientation respect to the sun or planets or the surface of the Earth.

3 DESIGN

The first step for the design took into consideration the shape of the structure to be utilized. In this case the structure selected for the moving part has a form of a typical rotor as shown in Figure 1.

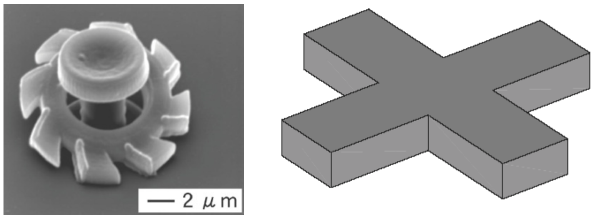


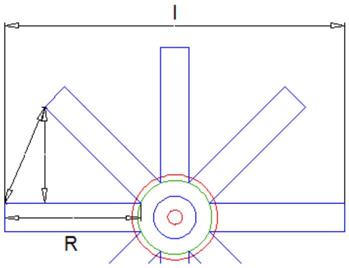
Figure 1 Typical rotor structures of Micromotors

This kind of structures has been utilized in the past without an elaborate design behind the implementation, giving "anecdotic" results [7]. The rotating part of the motor will be then mounted in a base which only purpose is to maintain the structure in place and to separate the rotating part from the base of the wafer. This base will also play a role in the reduction of the friction later on.

As it was mentioned in the introduction, when radiation pressure is used as an actuation method, one of the aspects to consider when it comes to increase the momentum transferred to any structure, is the angle of light coming in contact with its surface. In this case, the movement needed is tangential to the axis of rotation, making imperative that the incident light goes on that direction. A component of pressure in any other direction would contribute to the ongoing friction due to the weight of the structure.

Our design starts with using 4 μm^2 spot area for the incoming light. This selection defines the rest of the structure dimensions. To obtain maximum torque with the incident light, its incidence should be as far as possible from the center of the structure.

It is critical to define whether the structure during rotation will be away (no light comming) from the laser beam. This is due to the fact that the light spot is just a fraction of the arm's length, pointing to the end of the arm, to obtain a better value of torque. The addition of 4 more arms will increase the time that light incident will be in contact with the structure, increasing the time that the torque is being applied. As Figure 2 shows under this restriction an arm with a length bigger than 6.8 [μm] is needed. In this case, considering the fact that this has to go under micro machining process, an arm length of 9 [μm] is specified. With this value fixed, the rest of the dimensions are determined as showed in Figure 2.



$$R > \frac{2\mu}{(1 \quad \cos(45^\circ))} = 6.8\mu m$$

l = 2*9 μm + 6 μm
d = 3μm

Where d is the central diameter

Figure 2 Dimensions diagram

The final design of the structure has the form shown in Figure 3, where the red part represents the base of the motor.

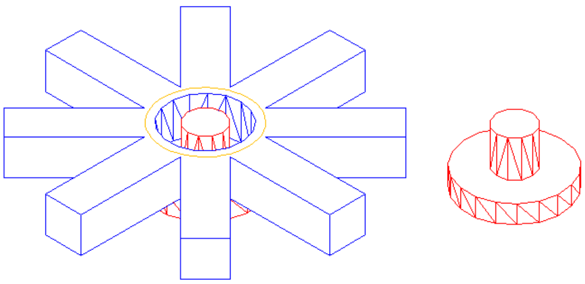


Figure 3 Final view of the structure

4 MATERIALS

The traditional material used in the fabrications of MEMs, mainly because of processing, is Silicon. The problem with this type of material, in a light driven structure, is its amount of reflectivity. Table 1 [8] shows reflectance index for different materials. As it is shown, Silicon reflectivity is around 20-60% depending on the frequency of the incident light.

Figure 4, on the other hand, shows a reflectivity of approximately 90% for Aluminium in almost all the spectra [9].

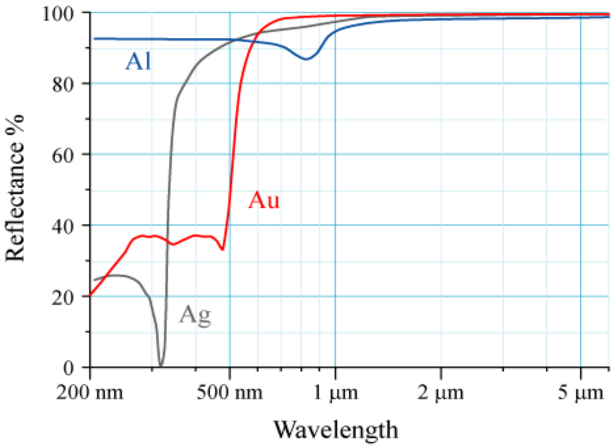


Figure 4 Reflectance of Aluminium compared to Gold

As it was mentioned in the introduction, Aluminium deposition is a common process in today's wafer fabrication and has become one of the materials of choice, besides gold, for micro mirrors. The main difference with gold is the density of the material.

As noted in Table 1, the density of gold is almost 10 times higher than Aluminium with similar reflective qualities. In this sense a material with less density would be more beneficial when it comes to reduce the friction torque due mainly to the weight of the structure.

Material	Density (g/cm3)	Reflection Index
Au	19.32	0.9
Ni	8.88	0.4
Si	2.33	0.2-0.6
Al	2.70	0.9

Table 1 Density and Reflection of metals considered

In terms of processing, Aluminium can be deposited in Silicon using Deep Reactive-Ion Etching (DRIE), but can incur in corrosion and electrostatic charging especially when it comes to rotating structures [10]. To avoid this problem, a coating material must be selected. A relatively new material, octadecylphosphonic acid (ODPA), not only lowers the already small value of friction, but also acts as a protective layer reducing the adhesiveness because of electric charging and possible corrosion. As Figure 5 shows, the material attaches itself chemically to the Aluminium keeping its adhesion to Aluminium longer that a non adhesive lubricant [11].

Due to the fact that the Aluminium structure will be in contact with the Silicon base when rotating, a coating material that ensures low friction and electrical insulation must be selected too. In this case the material of choice is a derivative of perfluoropolyoxyalkane, known as Z-DOL [12]. In this case, the polymer coating can be done using a dipping process [13].

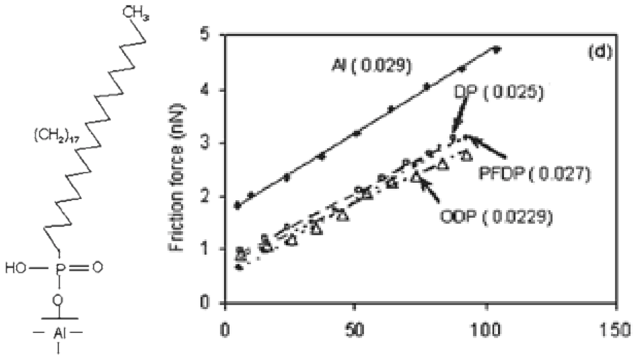


Figure 5 Chemical bonding between ODP and Aluminium (left) and friction coefficient (Right)

As Figure 6 shows Z-DOL has a very small friction coefficient and, by its nature, provides a barrier for electrostatic interaction too. Figure 7 shows how this material also bonds chemically to Silicon, providing a lasting lubrication and insulation effect.

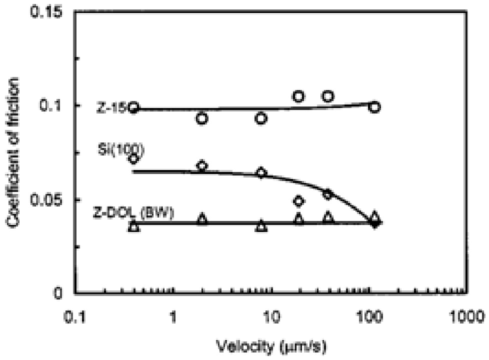


Figure 6 Z-DOL Friction coefficient

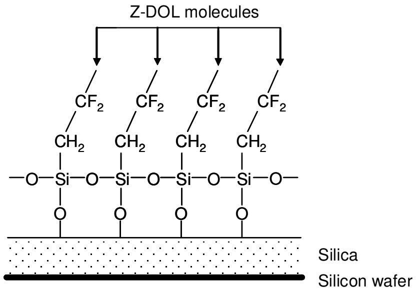


Figure 7 Chemical bonding between Si and Z-DOL

Once the rotating structure has been successfully coated with aluminium its rigidness makes unnecessary to keep the Silicon interior in place. If the silicon part of the structure is eliminated, the weight is reduced significantly, lowering the amount of friction present. This can be done easily with an etching process. The result is a hollow Aluminium structure as shows in Figure 8.

The final assembly of the individual parts can be done using a regular laser driven technique [14].

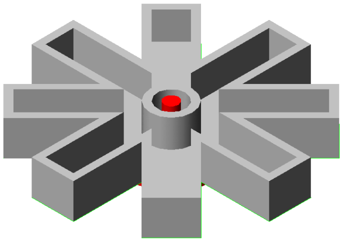


Figure 8 Aluminium hollow structure proposed

5 MODELING

To estimate the performance of this structure we need to model its behaviour when interacting with light.

One of the first steps is to calculate all the torques involved in the process. The friction torque is mainly due to the weight of the structure. The weight of the structure is obtained using the measurements detailed in Figure 9.

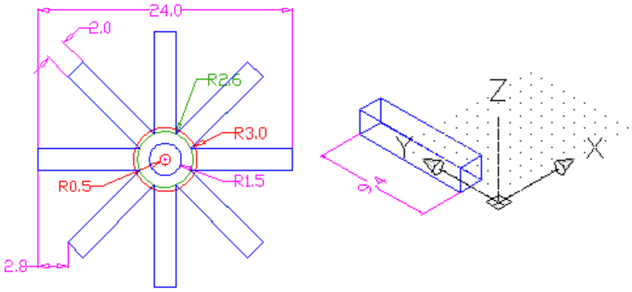


Figure 9 Dimensions of the final design

Using the mass of the structure, obtained with Equation 2, an expression for the friction torque is obtained.

$$M = 8 * \rho * \left(l - \left(\frac{d}{2} \right) \right) * h * w + \rho * \pi * \left(\left(\frac{d}{2} \right)^2 - \left(\frac{d_2}{2} \right)^2 \right) * h \qquad (2)$$

$$\tau_W = \frac{2 * M * g * \mu}{\left(\left(\frac{d_b}{2} \right)^2 - \left(\frac{d_2}{2} \right)^2 \right)} * \frac{\left(\left(\frac{d_b}{2} \right)^3 \quad \left(\frac{d_2}{2} \right)^3 \right)}{3} \qquad (3)$$

Where d=d+2*t d$_2$= d$_2$-2*t l=l+t w=w+2*t h=h+t and

M: mass of the structure
Ro: density of the material (aluminium)
d$_{b,d}$: external diameter of the structure (with coating)
h: height of the structure
d$_2$: Internal diameter (close to base pin)
t: Thickness of the coating
w: width of the arm
l: length of the arm

Equation 3 show that the friction torque as function of the structure distributed weight in the central portion of the structure. This torque is directly proportional to the gravitational acceleration, and as Equation 4 shows, its value depends on the altitude where the object is.

$$g = \frac{G * m_E}{(r_E + H)^2} \quad (4)$$

Where **G:** Gravitational acceleration Constant
m_E: Mass of the Earth
r_E: Radius of the Earth
H: Altitude where the acceleration is measured

Another torque to be considered is the torque due to interaction with air. The amount of viscous friction when rotating in presence of air depends on the amount of the surface exposed. The viscous friction torque over a disc rotating at a speed w is shown below [15].

$$\tau_{AD} = \left(\frac{3.87}{2}\right) * \rho * \upsilon^{0.5} * r^4 * \omega^{1.5} \quad (5)$$

Where: **ρ :** Density of air
υ : Viscosity of air
r : Radius of the structure

Using values for a typical laser with a spot size of 4 [μm^2] with an intensity of $5x10^6$ [W/m2], the radiation pressure torque is given by:

$$RP = \frac{2 * 0.9 * 5 \times 10^6}{3 \times 10^8} = 3 \times 10^{-2} \left[\frac{N}{m^2}\right]$$

$$\tau_{RP} = 1.2 \times 10^{-13} * 11 \times 10^{-6} = 1.32 \times 10^{-18} \; [N \cdot m]$$

Therefore, the final equation of movement is given by:

$$J * \frac{d\omega}{dt} = \tau_{RP} - \tau - \tau_{AD} = 5.5237 \times 10^{-23} * \frac{d\omega}{dt} \quad (6)$$

$$= 1.32 \times 10^{-18} - 6.7617 \times 10^{-20} * g - 1.9242 \times 10^{-22} * \omega^{1.5}$$

As shown in Figure 10, this provides a direct relationship between the speed of the structure and the altitude of the device.

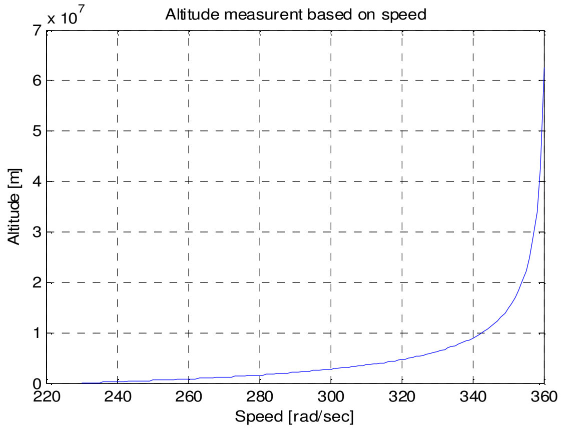


Figure 10 Altitude vs speed variation for the structure

6 CONCLUSIONS

The design of a micro motor driven by light used as a g-force meter has been presented. The novelty of this design resides in the hollow Aluminium structure that increases the radiation pressure's effect on movement. The reflectivity at different frequencies gives flexibility on the laser type selection process. The change on speed of the structure with gravitational acceleration variation, makes this design suitable for application where changes on g-force need to be detected, such as aircrafts' altimeters or planets proximity detection.

REFERENCES

[1] Compton, Arthur, "A Quantum Theory of the Scattering of X-Rays by Light Elements", Physical Review (vol. 21, 1923, p. 483-502).

[2] D. R. Koehler, "Optical actuation of micromechanical components," J. Opt. Soc. Am. B 14, 2197-2203 (1997)

[3] Williams, J A and Le, H R, "Tribology and MEMS", J. Phys. D: Appl. Phys. 39 (2006) R201–R214.

[4] Tambe, Nikhil, "Nanotribological Investigations of materials, coatings and lubricants for nanotechnology applications at high sliding velocities", PhD Thesis, Ohio State University 2005.

[5] Gauthier, R. C.,"Theoretical model for an improved radiation pressure micromotor", Appl. Phys. Letters – Sept. 30, 1996 -- Volume 69, Issue 14, pp. 2015-2017.

[6] NASA, http://solarsails.jpl.nasa.gov/index.html, Solar Sail Technology Development.

[7] L. Kelemen, S. Valkai, and P. Ormos, "Integrated optical motor," Appl. Opt. 45, 2777-2780 (2006).

[8] MatWeb, http://www.matweb.com/index.asp?ckck=1, The online materials information resource.

[9] Bass, M., Van Stryland, E.W. (eds.) Handbook of Optics vol. 2, McGraw-Hill (1994) ISBN 0070479747.

[10] Rahul Agarwal, Scott Samson, Sunny Kedia, and Shekhar Bhansali, "Fabrication of Integrated Vertical Mirror Surfaces and Transparent Window for Packaging MEMS Devices", JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 16, NO. 1, FEBRUARY 2007.

[11] B. Bhushan et Al, "Nanotribological characterization of perfluoroalkylphosphonate selt-assembled monolayers deposited on aluminum-coated silicon substrates", Microsystem Technologies, 2006, 12, 588-596.

[12] Kawaguchi M., Choi J., Kato K., and Tanaka K.,"A Study of Friction Properties of Zdol on Magnetic Disk Surface", IEEE Trans. on Magn. , Vol. 39, No. 5, Sept. 2003.

[13] Bhushan, Bharat, "Nanotribological Characterization of Molecularly-Thick Boundary Layers of Perfluoropolyether Lubricants for Applications to MEMS/NEMS by Atomic Force Microscopy", http://rclsgi.eng.ohiostate.edu/nlim/.

[14] A. S. Holmes and S. M. Saidam, "Sacrificial layer process with laser-driven release for batch assembly operations," ASME/IEEE J. of Microelectromechanical Systems, vol. 7, no. 4, pp. 416–422, 1998

[15] Coombs, T.A.; Samad, I.; Ruiz-Alonso, D.; Tadinada, K., "Superconducting micro-bearings", IEEE Transactions on Applied Superconductivity, Volume 15, Issue 2, June 2005 Page(s):2312 – 2315.