A High Voltage Solar Cell Array As An Electrostatic MEMS Power Supply

Jeong B. Lee, Zizhang Chen, Mark G. Allen, Ajeet Rohatgi
School of Electrical and Computer Engineering
Microelectronics Research Center
Georgia Institute of Technology
Atlanta, GA 30332-0250 USA

Rajeewa Arya
Solarex Corporation
Newtown, PA 18940 USA

Abstract

A high voltage hydrogenated amorphous silicon (a-Si:H) solar cell array which is optimized as a power source for electrostatic microelectromechanical systems (MEMS) is presented. A single test cell consists of a triple stack of p-i-n / p-i-n / p-i-n material and produces open circuit voltage (OCV) of 1.8~2.3 volts, short circuit current density (J_{sc}) of 2.8 mA/cm^2, and fill factor (FF) of 0.495. A series interconnected array of 100 of these cells (total array area of $1 cm^2$) has been produced in an integrated fashion and produces an array OCV of 150 volts, and short circuit current (I_{sc}) of 2.8 μA under Air Mass (AM) 1.5 illumination. To illustrate the use of this array as a MEMS power source, it has been packaged with a movable micromachined silicon (Si) mirror in a hybrid manner. The movable Si mirror is directly driven by the cell array electrical output, and the motion of the mirror plate has been observed reproducibly. Variation of light intensity and/or number of illuminated cells produces different array OCVs, thus enabling control of the deflection of the Si mirror by variation of incident light intensity.

I. Introduction

Since the power requirements for MEMS devices can be quite different from that for general electrical circuitry, additional external power connections or extra voltage conversion circuitry are needed. In addition, for autonomous operation, such as free-moving micro robotic systems and space-based MEMS, a self-contained on-board power supply is desirable. A direct on-board power supply [1] and an energy coupling method by using magnetic fields [2] have been introduced previously. Solar cells are also attractive as power sources for MEMS since they are easily integrated, and can therefore be fabricated easily as a self-contained on-board power supply. However, different solar cell power supplies must be developed to meet the different power requirements of various types of MEMS. Many different types of actuation principles have been proposed for MEMS. Most of the work has focused on electrostatic drive [3,4]; however, other principles have also been investigated [5]~[7]. Although some work has been done to decrease the electrostatic MEMS drive voltage requirement [8], electrostatic MEMS usually require drive voltages ranging from tens of volts to hundreds of volts and drive currents in the nA~μA range. These voltages and currents differ from those traditionally available from solar cell power supplies. Thus, if solar cells are to be used as power sources for electrostatic MEMS, modifications in traditional design methodology are required. This paper consists of design criteria for solar cells as a power source for electrostatic MEMS, solar cell array fabrication, experimental results for a single test cell, a series interconnected cell array, and an actuation demonstration using the cell array to drive a micromachined movable Si mirror.

II. Design Criteria

Several design criteria arise from the power requirements of electrostatic MEMS. First, the individual cells must be able to be connected in series with each other so that the interconnected cell array can meet the high voltage requirement. Second, high voltage output of single cells are desirable. Third, the array must be electrically isolated from the substrate to allow for isolated integration of the array, electrical circuitry, and the MEMS device. Finally, the array must consume a small area in order to minimize the overall size of the MEMS device. Note that in contrast to usual solar cell design criteria, maximization of the cell and/or array currents is not required. In order to facilitate series interconnection of cells, it is necessary to be able to make a connection from the bottom of the first cell to the top of the next cell. Therefore, thin film solar cells may be preferred in

0-7803-1833-1/94 $3.00

order to meet this criterion. Due to the device physics, J_{sc} increases as the bandgap of the material decreases; however, the OCV decreases with decreasing bandgap. The efficiency limits for several solar materials are shown in Figure 1.

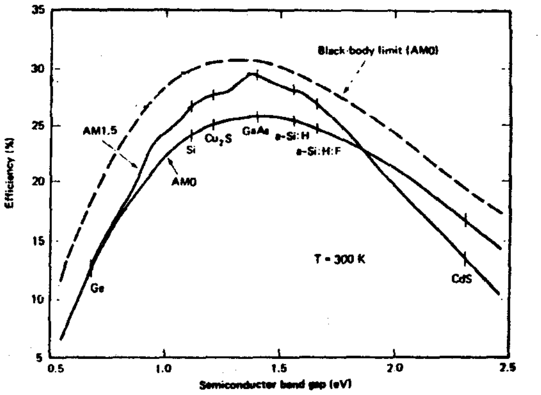


Figure 1. Solar cell efficiency limits as a function of the bandgap of the cell material [9]

To meet the high cell OCV requirement, higher band gap solar cells are preferred. Bulk wafer solar cells must be avoided since electrical isolation becomes difficult. Table 1 shows typical parameters for various highest efficiency solar cells.

	Single Crystal Si	Triple stacked a-Si	GaAs
OCV [V]*	0.702	2.51	1.045
$J_{sc}[mA/cm^2]^*$	40.7	7.2	27.6
Band Gap [eV]	1.21	1.5~1.6	1.42
Thickness[μm]	200~400	~1	2~4

Table 1. A parameter summary of the highest efficiency single crystal Si, a-Si, and GaAs. (quoted from Tables 1 and 6 of reference [10]*)

Since the single crystal Si solar cell is a bulk wafer cell, it is not compatible with the design criteria discussed above. In addition, since single crystal silicon is an indirect bandgap material, absorption of light requires relatively large cell thicknesses. The gallium arsenide (GaAs) cell has very high OCV and can be realized as a thin film; however, it is more expensive than the other materials. Taking into account several basic material properties, the hydrogenated amorphous silicon (a-Si:H) solar cells are the most attractive power supply for electrostatic MEMS for several reasons. Because of its relatively large bandgap (~1.5eV), cells made from this material have high OCVs of about 0.9 volts. Also, the absorption coefficients of a-Si:H are more than an order of magnitude larger than that of single crystal Si near the maximum solar photon energy region near 500nm. Accordingly, the optimum thickness of the active layer in a-Si:H solar cells (about 1μm) can be much smaller than that of single crystal Si solar cells. In addition, it is possible to stack multiple layers of a-Si:H to get stacked cells for very efficient utilization of substrate area. Finally, a-Si:H can be deposited on virtually any substrate and the cost of processing is relatively low.

III. A hydrogenated amorphous silicon solar cell

Since Carlson and Wronski [11] reported the first a-Si:H solar cells, there have been tremendous efforts and improvements. The primary reason for the popularity of this material is the ability to fabricate devices at low cost. Due to the deposition technology which has been developed for a-Si:H solar cells, this material can be deposited virtually on any low cost substrate, which insures low cost power generation. In order to achieve high efficiency cells, multi junction type a-Si solar cells have been proposed. Horizontally [12] and vertically [13] stacked multilayer type have both been introduced, in which a single cell has an OCV in excess of 2V. We have used same bandgap vertically stacked triple junction cells to make a single 'cell' with high OCV (in excess of 2V). These 'cells' are then interconnected horizontally in series to produce an array of very high voltage output. One of the major disadvantages of the a-Si:H solar cell in MEMS application is the temperature limitation. Due to its material property, the a-Si:H film begins to lose hydrogen at temperatures exceeding 400°C, irreversibly damaging the photovoltaic property of the cell. Several MEMS fabrication processes do not exceed this temperature limit (such as electroplating-based processes [14], [15]); however many of the common polycrystalline silicon processes will require the solar cell material to be deposited after the polysilicon deposition.

VI. Fabrication

A brief fabrication process of the solar cell array is shown in Figure 2. The process begins with a 3-inch <100> Si wafer as a substrate. A 4000Å layer of silicon dioxide (SiO_2) for electrical isolation is deposited onto the Si wafer by plasma enhanced chemical vapor deposition (PECVD) using silane (SiH_4) and nitrous oxide (N_2O). A 1μm layer of chromium (Cr) is deposited onto the SiO_2 layer by DC sputtering. The Cr layer is patterned to form a rear contact. A total of 1μm of a-Si:H p-i-n / p-i-n / p-i-n triple junctions are deposited by dc glow-discharge decomposition of SiH_4, diborane (B_2H_6), methane (CH_4) for the p-layer, SiH_4 for the i-layer, and SiH_4, phosphine (PH_3) for the n-layer respectively. An anti reflective coating is deposited onto this stack and the stack is then mesa etched in a 100% carbon tetrafluoride (CF_4) plasma at 150W incident power.

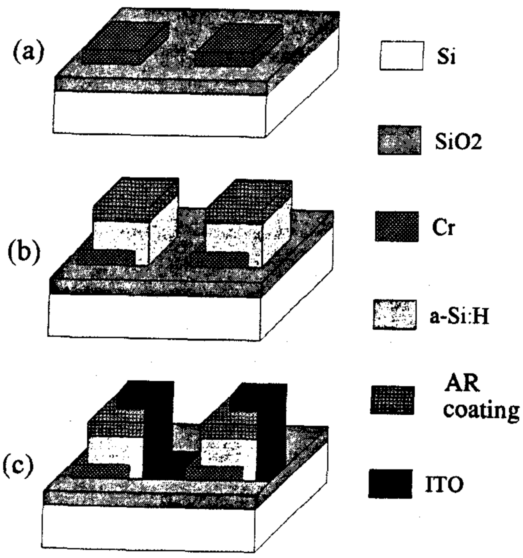


Figure 2. The fabrication process of triple junction solar cell array. (a) Cr rear contact; (b) a-Si:H triple junction solar cell and anti reflective coating; (c) ITO interconnection patterning

A 1200Å layer of indium tin oxide (ITO) is deposited using RF sputtering, and is patterned using 5% hydrofluoric acid (HF) to form a series electrical interconnection between individual cells. The sample is then annealed at 220°C for 20 min. using a rapid thermal processor (RTP) to decrease the sheet resistance of the ITO.

V. Experimental results

V-1. Triple stacked single cell test

A single vertical triple stack test cell was fabricated as described above and characterized under AM 1.5 conditions (the AM 1.5 condition is the standard solar cell test light intensity and energy distribution condition which corresponds to illuminated sunlight on the surface of the earth when the sun is at an inclination of 48.19° relative to overhead). The I-V characteristic curve of the triple stack cell under this illumination is shown in Figure 3. The OCV of a single a-Si:H solar test cell consisting of a triple stacked junction as described above is 1.8~2.3 volts, the short circuit current density J_{sc} is 2.8 mA/cm^2, and the fill factor (FF) is 0.495.

V-2. Series interconnected solar cell array test

After making series interconnection between individual solar cells as described above, the array OCVs were measured under varying light conditions.

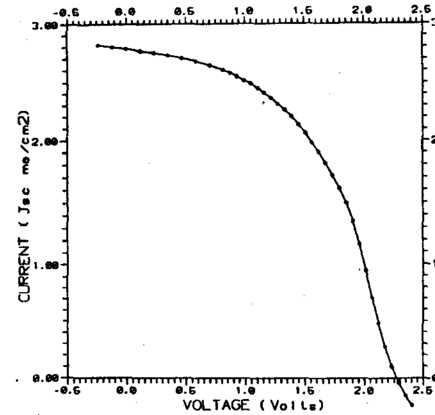


Figure 3. The I-V characteristics curve for triple stacked single a-Si:H solar cell

The array OCV measurement was carried out using a Keithley 236 Source Measurement Unit which had a $10^{14}\Omega$ input impedance to prevent any voltage drop in the voltage measurement due to loading by the meter. The array OCV as a function of the number of cells in series under varying illuminations is shown in Figure 4. As expected, the array OCV increases linearly as the number of cells in the array increases.

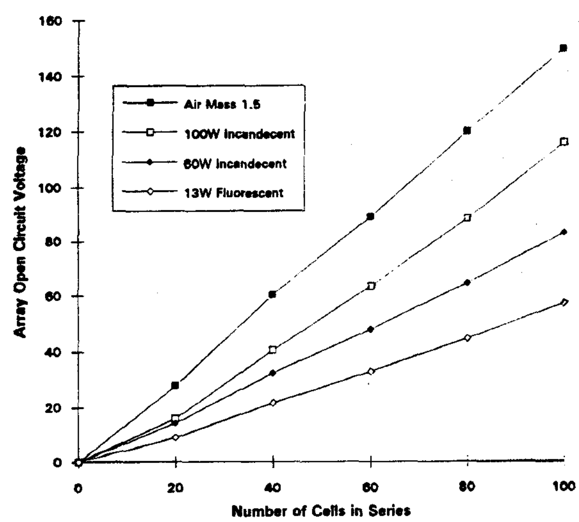


Figure 4. Array OCV as a function of number of cells in array, AM 1.5, 100W incandescent light bulb / 40 cm apart, 60W incandescent light bulb / 40 cm apart, 13W fluorescent lamp / 40 cm apart

For a 100 cell array (total array area of $1cm^2$), the achievable maximum OCV is as high as 150 volts under AM 1.5. Even under the relatively poor illumination of a 13W fluorescent lamp which is located at 40 cm above the cell array, an OCV of 57V was attained. When the number of series-connected cells in the array is kept constant, the array OCVs increase as the light intensity increases. The variation of array OCV as a function of light intensity variation (actually varying the distance between the cell array and the light source) has been measured by using a PASCO 9152B photometer. Figure 5 shows the resultant OCV as a function of illuminance (lux), where 1 lux is equal to 1 lm/m^2 at a wavelength of 560 nm [16].

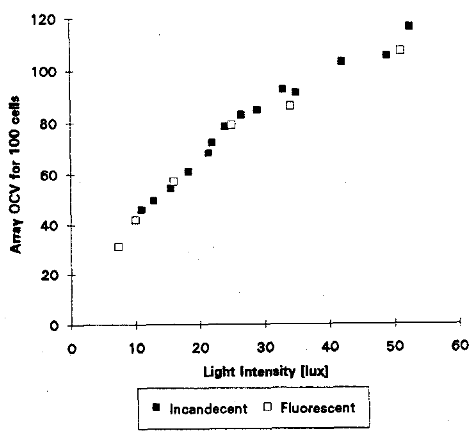


Figure 5. Array OCV as a function of photometric light intensity which has been carried out by varying the distance between light sources and cell array

Even though the spectral response of the photometer does not exactly match that of the incandescent and fluorescent lamps, the measured light intensities give relative references. The results described in Figures 4 and 5 illustrate that the solar cell array developed in this paper is applicable as a high voltage power supply for many electrostatic based MEMS even under ordinary room light conditions.

V-3. Demonstration of electrostatic MEMS operation using the solar cell array

The series interconnected array of one hundred a-Si:H solar cells was bonded and packaged on a standard flat-pack carrier with a prototype MEMS device, a micromachined movable Si mirror suspended at its center by flexible polyimide supports [17]. The packaged device is shown in Figure 6. The movable Si mirror is directly driven by the cell array output. The electrostatic drive voltage from the array is placed between the movable plate and the underlying metallic surface (ground) of the flat-pack carrier. A polyimide (Kapton) tape has been placed underneath the MEMS die to prevent electrical shorting between the mirror plate and the bottom ground. The deflection of the tip of the Si mirror was measured by focusing on the tip of the mirror using a Nikon MM-11 Measurescope and measuring the deflection of the microscope head necessary to keep the deflecting tip in focus.

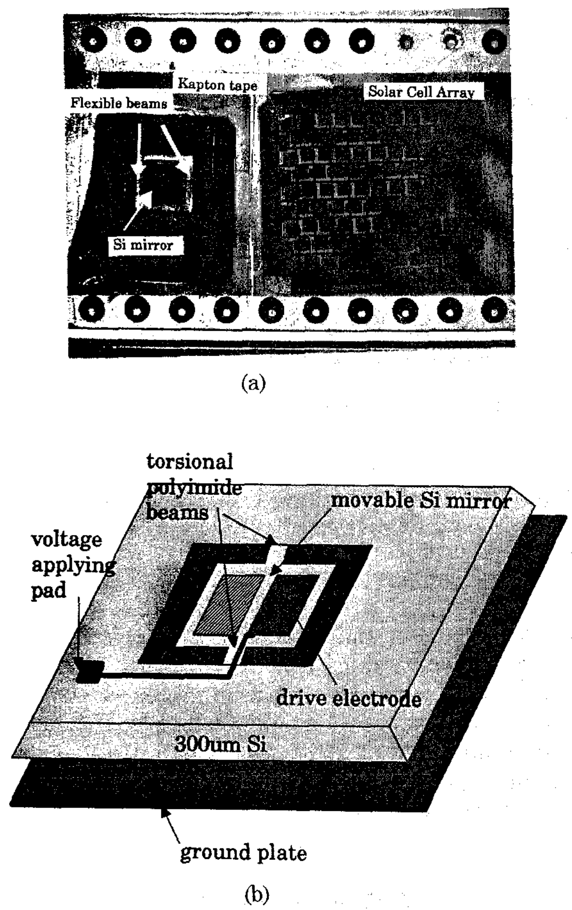
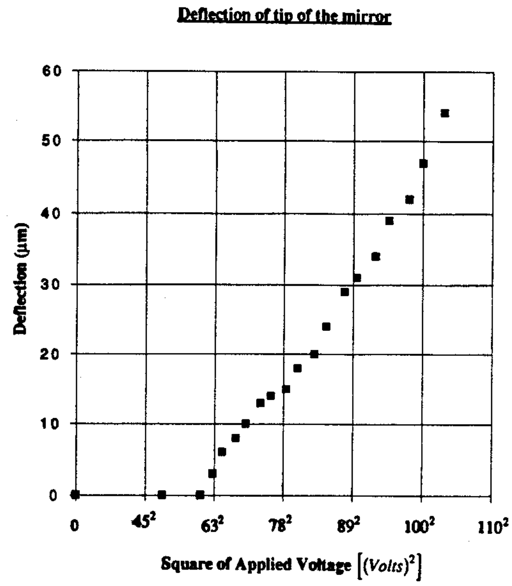
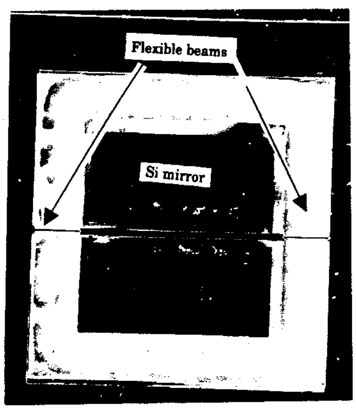


Figure 6. (a) A photograph of a series interconnected 100 cell array (total array area of $1cm^2$) packaged with a movable Si mirror; (b) A schematic diagram of the movable Si mirror.

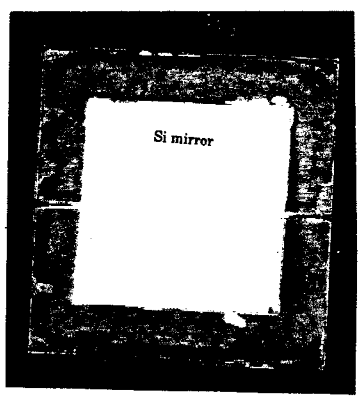
Motion of the Si mirror plate was observed from approximately 63 volts array output. As expected for this type of electrostatically-driven capacitive actuator, the deflection of the tip of the mirror is linearly proportional to the square of the output voltage of the cell array up to 105 volts (where the voltage variation was obtained by varying the position of the light source relative to the cell array), at which time the movable plate snapped to the bottom electrode. The detailed plot of the deflection of the tip of the mirror is shown in Figure 7. This behavior could be reproducibly observed.



(a)



(b)



(c)

Figure 7. (a) Deflection of the tip of the Si mirror as a function of square of applied output voltage of an a-Si:H solar cell array; (b) A photograph of the Si mirror plate without deflection up to a drive voltage of 63V; (c) 54µm tip deflection near a drive voltage of 105V.

VI. Conclusions

An a-Si:H solar cell array with multiple number of cells in series has been fabricated and used as a power supply for electrostatic MEMS in a hybrid manner. An open circuit voltage as high as 150 volts under AM 1.5 conditions of this small size solar cell array ($1cm^2$) has been achieved. The electrical power output of the solar cell array is well matched to the power requirements of electrostatic MEMS. Variation of the incident light intensity produces a variation of the array OCV, thus allowing control of electrostatic actuation based on incident light intensity. This solar cell array can also be used for any device which requires voltages ranging from several volts to above one hundred volts with small currents in the nA~µA range. Due to the material properties of a-Si:H, the array cannot be used at temperatures exceeding 400°C. The hybrid micro-system demonstration is a stepping stone to achieve a fully integrated microsystem including a solar cell array as a power supply and a MEMS device as a sensor and/or actuator.

Acknowledgment

This work is supported in part by the National Science Foundation under grant ECS-9117074. Microfabrication except as noted below was carried out in the Georgia Tech Microelectronics Research Center. The support of the staff of the Pettit Microelectronics Research Center at Georgia Tech is acknowledged. The amorphous silicon deposition was carried out at Solarex, Inc., and the fabrication of the micromachined silicon mirror was carried out at the Massachusetts Institute of Technology. The open circuit voltage and short circuit current measurements were made with the help of Mr. Myung H. Lee at Georgia Tech. The valuable technical discussions with Dr. Chong H. Ahn, Dr. A. Bruno Frazier, and other microsensor and micro-actuator group members at Georgia Tech are greatly appreciated.

References

[1] J.B. Bates, G.R. Gruzalski, and C.F. Luck. "Rechargeable Solid State Lithium Microbatteries", in *Proceeding 6th IEEE Workshop on Micro Electro Mechanical Systems* (Fort Lauderdale, FL), pp.82-86, Feb. 1993

[2] H. Matsuki *et al.*, "Implantable Transformer for an Artificial Heart Utilizing Amorphous Magnetic Fibers", *Journal of Applied Physics*, vol.64, pp.5859-5861, 1988

[3] W.C. Tang, T.H. Nguyen, M.W. Judy, and R.T. Howe, "Electrostatic Comb-Drive of Lateral

Polysilicon Resonators", *Sensors and Actuators*, vol. A21, no.1-3, pp.328-331, Feb. 1990

[4] L.S. Fan, Y.C. Tai, and R.S. Muller, "IC-processed Electrostatic Micromotors", *Journal of Micromechanics and Microengineering*, vol.2, no.4, pp.225-228, Dec. 1992

[5] C.H. Ahn and M.G. Allen, "A Fully Integrated Surface Micromachined Magnetic Microactuator with a Multilevel Meander Magnetic Core", *Journal of Micro Electro Mechanical Systems*, vol.2, no.1, pp.15-22, Mar. 1993

[6] W. Riethmuller and W. Benecke, "Thermally Excited Silicon Microactuators", *IEEE Transactions on Electron Devices*, vol.ED-35, pp.758-, 1988

[7] K.R. Udayakumar *et al.*, "Ferroelectric Thin Film Ultrasonic Micromotors", in *Proceeding 4th IEEE Workshop on Micro Electro Mechanical Systems* (Nara, Japan), pp.109-113, Jan. 1991

[8] T. Hirano, T. Furuhata, K.J. Gabriel, H. Fujita, "Design, Fabrication, and Operation of Submicron Gap Comb-Drive Microactuators", *Journal of Micro Electro Mechanical Systems*, vol.1, no.1, pp.52-59, Mar. 1992

[9] M.A. Green, "Solar Cells: Operating Principles, Technology, and System Applications",*Prentice-Hall, Inc.*,Englewood Cliffs, N.J., p.89, 1982

[10] L.L. Kazmerski, "Status and assessment of Photovoltaic Technologies", *International Materials Review*, vol.34, no.4, pp.185-210, 1989

[11] D.E. Carlson and C.R. Wronski, "Amorphous Silicon Solar Cell", *Applied Physics Letter*, vol.28, no. 11, pp.671-673, Jun. 1976

[12] Y. Hamakawa, H. Okamoto, and Y. Nitta, "A New Type of Amorphous Silicon Photovoltaic Cell Generating More Than 2.0V", *Applied Physics Letter*, vol.35, no.2,pp.187-189, Jul. 1979

[13] S. Guha *et al.*, "A novel design for Amorphous Silicon Alloy Solar Cells", *Proceeding 20th IEEE Photovoltaic Specialists Conference*, pp.79-84, 1988

[14] E.W. Becker *et al.*, "Fabrication of Microstructures with High Aspect Ratios and Great Structural Heights by Synchrotron Radiation Lithography, Galvanoformung, and Plastic Moulding (LIGA Process)", *Microelectronic Engineering*, vol.4, pp. 35-56, 1986

[15] A.B. Frazier and M.G. Allen, "Metallic Microstructures fabricated Using Photosensitive Polyimide Electrplating Molds", *Journal of Micro Electro Mechanical Systems*, vol.2, no.2, pp.87-94, Jun. 1993

[16] F.L. Pedrotti, S.J. Leno, and S. Pedrotti, "Introduction to Optics", *Prentice-Hall, Inc.* ,Englewood Cliffs, N.J., pp.10-14, 1993

[17] M.G. Allen, M. Scheidl, and R.L. Smith, A.D. Nikolich, "Movable Micromachined Silicon Plates with Integrated Position Sensing", *Sensors and Actuators*, vol.A21, no.1-3, pp.211-214, Feb. 1990