SURFACE-MICROMACHINED AND HIGH-ASPECT RATIO ELECTROSTATIC ACTUATORS FOR AERONAUTIC AND SPACE APPLICATIONS : DESIGN AND LIFETIME CONSIDERATIONS

P. Vescovo*, E. Joseph*, G. Bourbon*, P. Le Moal*, P. Minotti*,

C. Hibert**, G. Pont***

*Laboratoire de Mécanique Appliquée R. Chaléat (LMARC)/ UMR CNRS 6604 / IMFC FR 0067
**EPFL Center of Micro- Nano- Technnology
***Centre Spatial de Toulouse (CNES)
LMARC- 24 Chemin de l'Epitaphe 25000 Besançon
Phone : 33.3.81.66.60.15
Fax : 33.3 81.66.67.00
e-mail: patrice.minotti@univ-fcomte.fr

ABSTRACT

This paper focuses on recent advances in the field of MEMS-based actuators and distributed microelectro-mechanical systems (MEMS). IC-processed actuators (e.g. actuators that are machined using integrated circuit batch processes) are expected to open a wide range of industrial applications on the near term. The most promising investigations deal with high-aspect ratio electric field driven microactuators suitable for use in numerous technical fields such as aeronautics and space industry.

Because the silicon micromachining technology have the potential to integrate both mechanical components and control circuits within a single process, MEMS-based active control of microscopic and macroscopic structures appears to be one of the most promising challenges for the next decade. As a first step towards new generations of MEMS-based smart structures, recent investigations dealing with silicon mechanisms involving MEMS-based actuators are briefly discussed in this paper.

1. INTRODUCTION

During the last decades, electrical engineers contributed to the development of the MEMS technology, and today, nobody doubts the feasibility of sophisticated mechanisms using IC-fabrication techniques. However, the involvement of mechanical engineers has become indispensable for investigating efficient driving mechanisms on the micrometer scale and improving the design rules of MEMS-based actuators and systems [1].

Recent advances in the design of IC-processed mechanisms are discussed in this paper. The communication focuses in particular on two fundamentally different driving mechanisms, with a special emphasis on reliability and lifetime characteristics:

- *Surface-micromachined electrostatic actuators involving stator/ rotor contact interactions* will certainly open a wide range of industrial applications, but are still subjected to parasitic phenomena such as wear and stiction that still prohibit their industrial development on the near term.
- High-aspect ratio electric field driven actuators, that can today achieve both efficient output driving characteristics and high reliability which is usually required for most of space applications.

2. RECENT TRENDS IN THE DESIGN OF IC-PROCESSED ACTUATORS AND MECHANISMS

2.1 Multilevel polysilicon micromechanisms

Despite inherent shaping limitations, the polysilicon surface micromachining technology (SMT) has, as its basis, the manufacturing methods and tool sets used to manufacture the integrated electronic circuit. Therefore, polysilicon surface-micromachining remains the most appropriate method for manufacturing sophisticated MEMS components such as microactuators.

The drawback to earlier IC-processed electrostatic actuators, even with small gaps, was the low force and torque obtainable from low-aspect ratio polysilicon components. In addition, integrated force amplification mechanisms such as multi-level polysilicon gear-speed-reductions were prohibited for a long time, until Chemical Mechanical Polishing (CMP) was introduced to surface micromachining.

Historically, the primary obstacles to multi-level polysilicon fabrication were related to the severe wafer topography generated by the repetition of film depositions and etching. However, CMP applied to multi-level surface micromachining has largely removed these issues and opened significant avenues for device complexity [3].

The primary devices to benefit from multi-level SMT are micromechanical actuators. Thus, the SUMMIT V Technology (e.g. 5 polysilicon structural levels) recently developed at *Sandia National Laboratories*, has aided in producing higher-force actuators through monolithic integration of complex mechanisms such as polysilicon gear-boxes [4].

However, as a MEMS fabrication technology, low aspect ratio polysilicon surface-micromachined structures tend to be most sensitive to stiction. This is mostly due to the surface-to-volume ratio of polysilicon components and the scaling behavior of various surface effects on the micrometer scale. Accordingly, experience with geared polysilicon mechanisms pointed out that the device surface phenomena of stiction, friction and wear present the greatest impediment to further industrialization of electric field driven IC-processed actuators [4].

2.2 Surface-micromachined electrostatic actuators using contact interactions on the wafer level

The height-to-width aspect ratio has been for a long time considered to be the main design parameter of IC-processed electrostatic actuators, leading to various high-aspect ratio microfabrication methods such as discussed in section 2.3. However, one can imagine other optimal design rules for highly-efficient electrostatic actuators using low-aspect ratio surface-micromachined polysilicon structures. As an example, micrometer thick IC-processed electrostatic actuators developed at IMFC/ LMARC –Besançon recently pointed out unusual mechanical performances by using "*contact interactions*", instead of conventional "electric field interactions".

As shown in Fig.1, electrostatic actuators using contact interactions operate using a friction-based mechanical energy transduction which takes place across a rigid stator (e.g. the wafer) and a flexible polysilicon rotor.

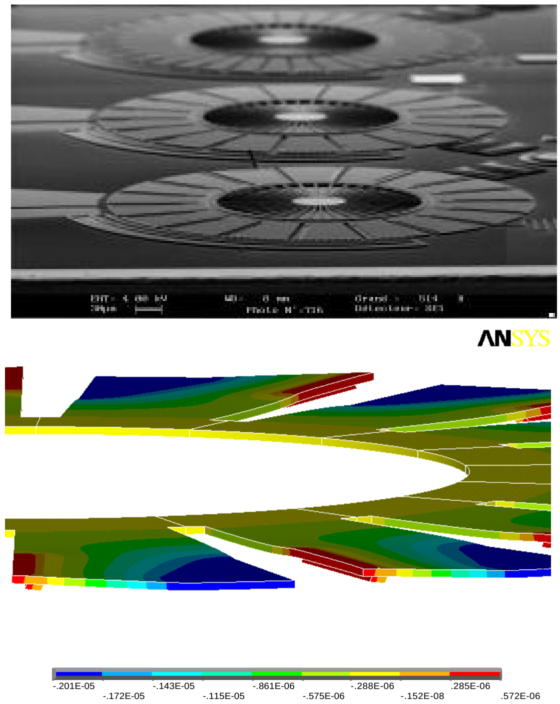

Fig.1 Surface-micromachined electrostatic actuators using contact interactions on the wafer level

The rotor is a flexible polysilicon disk plate on which radial grooves are etched in order to shape elementary actuation cells. Each actuation cell is actuated by applying a driving voltage on an annular underground electrode located on top of the wafer surface. Micrometer height contact plots that are embedded into the actuation cells provide contact asymmetries which are fundamentally needed to actuate the stepping motion of the rotor. By applying a square voltage across the driving electrodes (e.g. across the stator/ rotor interface), the electrostatic pressure periodically twists the annular array of actuation cells. The corresponding rotation of the distributed contact plots therefore provides nanometer stepping motion that can be easily controlled through open loop frequency control.

Annular IC-processed micromotors shown in Fig.1 obey the Coulomb friction Law and thus develop an high-driving torque that linearly depends on the electrostatic pressure exerted onto the flexible polysilicon rotor. Because of the non-linear mechanical behavior which results from progressive clamping effects, the electrostatic pressure applied to the rotor can reach several tens MPa, against typically 10^{-2} MPa using conventional parallel-plate capacitors.

Accordingly, micrometer size annular micromotors supplied with electrical square pulses having +/- 100 Volts peak amplitude develop a nominal driving torque on the order of 1.5 µNm [5], while the maximum output torque can be as high as 4 µNm under 200 Volts driving voltage (see Fig.2). Such an unusual driving torque is roughly 1,000 to 10,000 times the output torque usually developed using conventional electric field driven actuators having a similar size, and addressed with a similar voltage.

On-chip torque measurements have been recently achieved through electrostatic probing of polysilicon actuators on the wafer level. Because polysilicon is known to be a brittle material, actuators had thus been combined with purely elastic polysilicon torque sensors machined in a common process flow [5]. Monolithic test structures such as shown in Fig. 2 led to ideal boundary conditions for getting micrometer size actuator loading characteristics. Elastic torque sensors involving polysilicon beam arrays embedded into the silicon substrate (wafer), were monolithically connected to the polysilicon rotor. Accordingly, external mechanical loading that was applied from the elastic torque sensor deflection has been directly measured as a function of the angular stiffness of the polysilicon beam array. More recently, output mechanical power limits have been investigated using an high-frequency CMOS camera combined with a specific image analysis software [6].

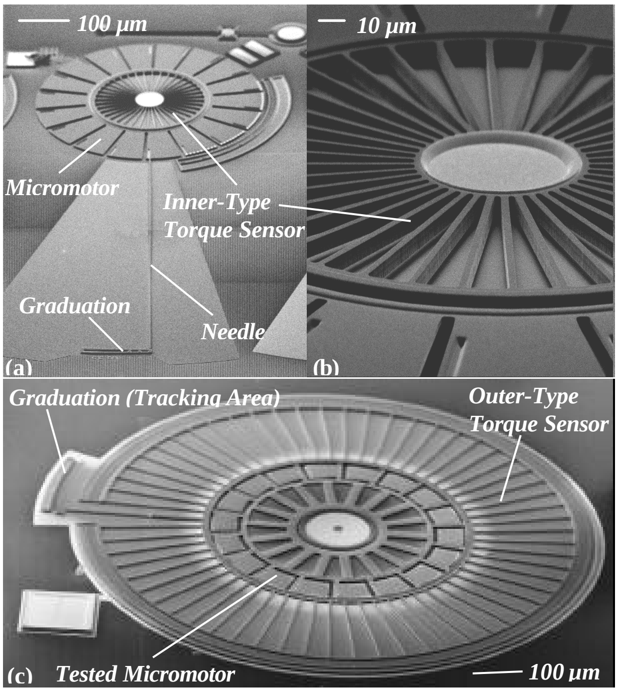

Fig.2 (a) and (b): Micrometer size test structure combining annular electrostatic micromotors with inner-type and outer-type elastic torque sensors, (c) magnified SEM micrograph showing an inner-type polysilicon torque sensor. After [5] and [6].

Figure 3 points out the dynamic behavior of a ϕ500 microns annular electrostatic actuators using stator/ rotor contact interactions. The driving frequency supplied to the actuator has been gradually incremented from 20 kHz, up to 100 kHz, while the amplitude of the driving voltage was maintained to a maximal level of 200 Volts. The rotation speed of the tested actuators decreases as a function of the loading torque which progressively brakes the rotor until stopping.

Experimental curves plotted in Fig. 3 have been obtained by triggering acquisitions of images sequences with electric signals supplied to the tested actuators. Very short test durations (e.g. on the order of 5 milliseconds when the driving frequency is increased up to a maximum of 100 kHz, have been recorded by switching the record speed up to 1828 images/sec.

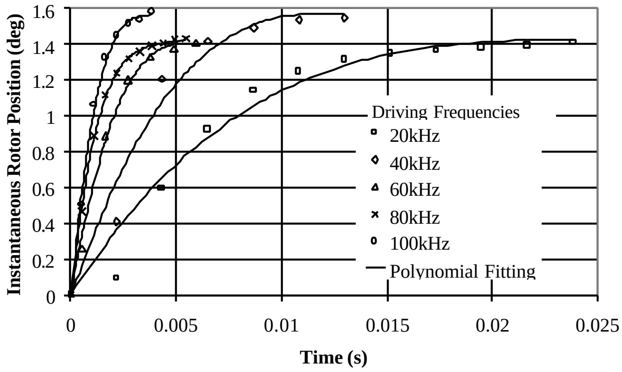

Fig.3 Dynamic behavior of the actuator for various driving frequencies in the range 20 to 100 kHz [6].

Taking into account the non-linear angular stiffness of the torque sensor, Fig. 4 shows the resulting torque/ speed characteristics as well as the output mechanical power of ϕ500 microns polysilicon micromotors. The maximal driving torque remains the same whatever the driving frequency that is supplied onto the driving electrode, while the actuator rotation speed linearly depends on the input driving frequency. Accordingly, output mechanical power linearly depends on the driving frequency, according to experiments reported in Fig.4 (b).

The maximal output mechanical power reaches 18 µWatts, thus, taking into account the overall mass of the rotor (which is on the order of $2\ 10^{-10}$ kg), the maximal output power per mass unit of the tested actuator is approximately 100 Watts/gr. Such an unusual mechanical performance, which is roughly 100 to 1000 times the output power/mass ratio of conventional macroscopic size electromagnetic actuators, opens new actuation perspectives in the field of MEMS-based active control of structures [1]. However, recent experiments pointed out surface related phenomena such as stiction, friction and wear which still limit the operating lifetime of electrostatic actuators using contact interactions, prohibiting numerous industrial applications on the near term.

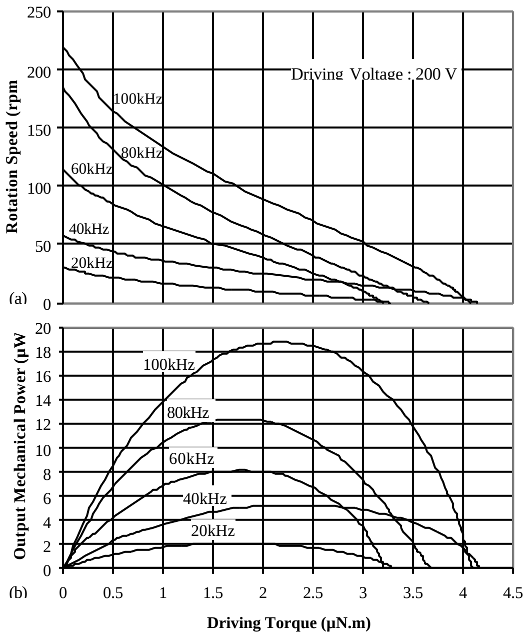

Fig.4 (a) Torque/ speed characteristics of electrostatic micromotors using stator/ rotor contact interactions, and (b) output mechanical power as a function of the driving frequency.

2.3. High-aspect ratio electric field driven actuators

The height-to-width aspect ratio of silicon-based actuators is another extremely important design parameter for at least two reasons. First, for a fixed capacitive gap, the actuator output force (or output torque) is linearly proportional to the structural height and therefore increases linearly with aspect ratio. Second, it is important that any uncontrollable cross-axis resonance be well above the servo bandwidth [7]. Modern methods for producing high-aspect ratio structures have thus been recently developed so as to meet the design requirements for efficient electric field driven actuators. The most promising machining approaches deal with high aspect ratio combined poly & single-crystal silicon (HARPSS), as well as silicon on insulator (SOI) technology.

The history of SOI development started in the 1960's, when the SOI structure was created to develop the first microprocessor using silicon-on-sapphire (SOS). Since that time, various methods of forming the SOI structure on a silicon wafer were proposed. In 1998, IBM announced a breakthrough in manufacturing a high-performance, low power CPU using the SOI technology. The SOI CPU delivers 30% faster performance and two-thirds lower power than a bulk-silicon CPU. This achievement marked a turning point in the 30-year history of SOI research and development. Today, the SOI wafers can also be ordered according to the MEMS designer's specifications. In such a case, the SOI layer (e.g. the single crystal silicon layer on top of the insulated layer) is usually much thicker (e.g. a few tens microns) than that used in the semiconductor industry. Thus, SOI wafers ordered by MEMS designers consist of device wafer, buried oxide, and handle wafer. Device wafer (e.g. SOI layer) has very low resistivity and is polished to 10-150 microns for getting high-aspect ratio structural elements. Buried oxide is typically 2 micron thick so that it is sacrificially etched at a reasonable time and the device wafer does not stick to the substrate wafer in the release process. Substrate wafer has the same low resistivity as the device wafer to eliminate parasitic capacitance by grounding the MEMS structures.

The recent introduction of the SOI technology in MEMS manufacturing methods significantly improved the mechanical performances of IC-processed sensors and actuators. Since former surface-micromachined actuators involved a polycrystalline silicon film of only about 2 micron thick in their structure (see sections 2.1 & 2.2), they were subjected to sticking, cross-axis parasitic resonance, low capacitance and unusable driving forces (except for actuators using contact interactions). So, high-aspect-ratio single crystal silicon structures today available from SOI wafers open new design perspectives for further IC-processed actuators and mechanisms. Taking advantage of the considerable increase of the actuator's bending stiffness which drops as the third power of the polysilicon structure height, the size of "SOI" actuators has been significantly increased, compared with former low-aspect ratio polysilicon actuators. Thus, millimeter scale actuators fabricated from SOI wafers are now suitable for concrete industrial applications such as shown in Figs. 5, 6 and 7.

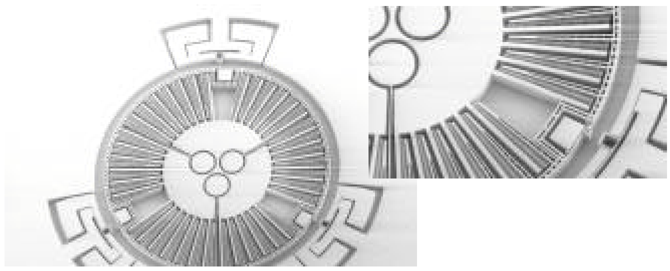

Fig.5 High-aspect ratio electric field driven SOI actuator for active control of read/write magnetic head.

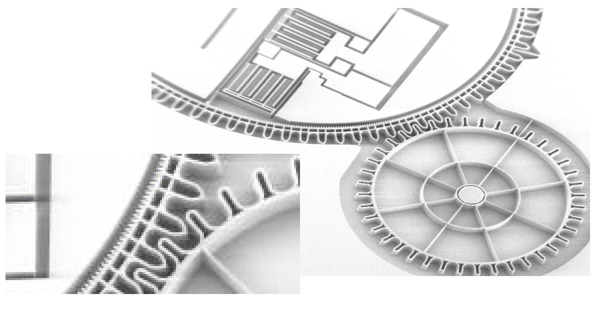

Fig.6 Self-actuated space mechanism including gear box reduction (components are 50 microns thick).

High-aspect ratio single crystal silicon mechanisms today available from SOI technology also open new perspectives in numerous technical fields such as space industry. As an example, Figs. 6 and 7 show SOI-based mechanisms that have been successfully designed in order to potentially actuate various mechanical functions in further nano-satellites.

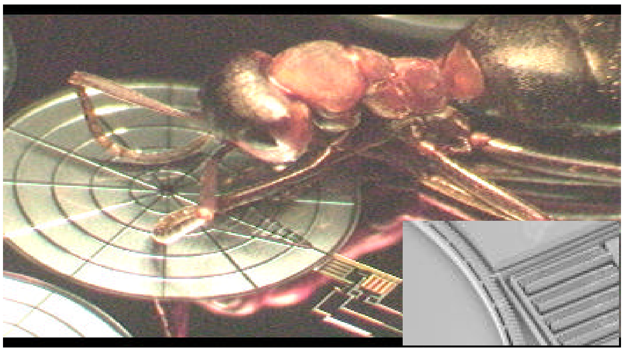

Fig. 7 Ant playing with an high-aspect ratio MEMS-based mechanism realized on an SOI wafer. The wheel (ƒ 2 millimeters/ 50 microns thick) integrates several hundreds teeth.

The output torque delivered through the integrated space mechanism shown in Fig.7 is as high as 2.5 µNm under 100 Volts driving voltage. In addition, the actuator has been successfully operated during more than 50 days. During that running time, the self-assembled driving mechanism successfully engaged 1,000,000,000 teeth, leading to operating sequences on the order of 1,500,000 rotor revolutions. In addition, the rotation speed can be easily modulated from very low speed (e.g. ~1 revolution per day), up to high rotation speed on the order of a few thousands rpm. Current cut-off frequency is 10 kHz, meaning that up to 10,000 teeth can be successfully engaged within 1 second. Furthermore, SOI actuators and mechanisms can be easily duplicated through parallel processing on a single silicon wafer, leading to low cost production. Thus, economic aspects combined with optimal driving characteristics and high reliability will certainly lead to concrete applications dealing with aeronautics and space on the near term. However, introduction of SOI actuators within space mechanisms remains challenging with respect to mechanical interfacing with the load as well as to driving voltage :

- Current high driving voltage operating mode requires specific electronics to address actuators on the wafer level,
- Assembling constraints related to the hybridization of MEMS actuators on external mechanisms will be also severely challenging in order to develop fully integrated systems for aeronautics and space applications.

3. From MEMS-based components to IC-processed distributed systems

Because the silicon micromachining technology have the potential to integrate both mechanical structures and control circuits, MEMS-based active control of structures therefore appears to be one of the most promising challenges of microsystems technology (MST). Thus, numerous projects are being developed in order to enhance design and machining approaches for new generations of MEMS-based smart structures involving arrays of silicon mechanisms. Considerable efforts began a few years ago so as to demonstrate techniques that will enable distributed MEMS-based arrays of sensors, actuators and computational elements embedded within materials and on surfaces, to enhance and control the behavior of sophisticated structures [8]. Current research includes the development of software and architectures for coordinating the actions of large number of distributed sensors and actuators. New manufacturing methods are also investigated so as to bring MEMS-style batch fabrication to bear on macro-scale objects. The futurist ideal system is one in which large numbers of sensors and actuators will be able to work relatively independently to achieve global performance criteria such as structural stability and mechanical modulation of surface properties. As an example, the concept of large panels involving thousands of actuators moving elementary radiators in order to modulate dissipation of calories as a function of the instantaneous position of a satellite is a nice example of what MEMS-based distributed systems will provide for space satellites on the near future. There is no doubt that interactive MEMS-based distributed systems will find numerous other developments that will strongly depend on the thinking of mechanical engineers working in the field of aeronautics and space.

4. Conclusion

Since former surface-micromachined electric field driven actuators involved polycristalline silicon films of only about 2 micron thick in their mechanical structure, they were subjected to sticking, parasitic bending effects, cross-axis resonance, low capacitance and hence, unusable driving forces. Emerging electrostatic actuators involving contact interactions on the wafer level recently pointed out unusual mechanical performances compared with former surface-micromachined actuators, but they are still subjected to parasitic stiction, leading to restricted lifetime characteristics that prohibit most of industrial applications on the near term. The recent introduction of the SOI technology in MEMS manufacturing methods significantly improved the mechanical performances of electric field driven actuators. Because

SOI-based actuators operate without mechanical contact between fixed and moving combs, they are not subjected to wear and stiction, therefore leading to high reliability. In addition, such actuators exhibit an aspect ratio considerably higher than that of surface-micromachined electrostatic actuators, leading to efficient driving characteristics.

REFERENCES

[1] Minotti, P. et al., *Responsive systems for active vibration control, NATO Science series-II Mathematics, Physics and Chemistry, Vol.85,* edited by Kluwer Academic Publishers, 2002, 394p.

[2] Berlin, A.A., MEMS-based active control of macro-scale objects, *Semiannual Technical Progress Report n° DABT63-95-C-0025, DARPA 1997.*

[3] Sniegowski, J.J., Chemical-mechanical polishing enhancing the manufacturability of MEMS, *SPIE Micromachining and Microfabrication Process Technology,* Austin, SPIE Vol. 2879, 1996, pp.104-115.

[4] Sniegowski, J.J., Multi-level polysilicon surface-micromachining technology : applications and issues, *ASME International Mechanical Engineering Congress,* Atlanta, Vol. 52, 1996, pp. 751-759.

[5] Minotti, P., Le Moal, P. *Evolutions récentes des lois de design des microactionneurs électrostatiques, Traité EGEM Microactionneurs électroactifs,* edited by Hermès-Lavoisier, 2002, pp. 109-147.

[6] Walter, V., Le Moal, P., Minotti, P., Joseph, E, Bourbon, G. Investigation of output mechanical power limits on high-torque electrostatic actuators using high-frequency CMOS camera combined with image processing software, *JJAP,* Vol. 41, 2002, pp. 424-427.

[7] Horsley, D.A., Cohn, M.B., Singh, A., Horowitz, R., Pisano, A., Design and fabrication of an angular microactuator for magnetic disk drives, *Journal of Microelectromechanical Systems* Vol.7, 1998, pp.141-148

[8] Fujita, H., A decade of MEMS and its future, *IEEE Proceedings on Micoelectromechanical Systems,* Nagoya, 1998, pp. 1- 8.

Back to Contents