Characterization of a 2-dof MEMS nanopositioner with integrated electrothermal actuation and sensing capability

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***Abstract*—This paper reports a new 2-degree of freedom (2-dof) micromachined MEMS nanopositioner with the actuation and sensing elements on the same chip. The features of this new MEMS device are: its 2-dof (x-y axis) motion capability, the achievement of bi-directional movement (positive and negative displacement) along each axis thanks to the use of Z-shaped electrothermal actuators, and the measurement of x-y displacements by integrated electrothermal sensors positioned underneath the moving stage. The experimental characterization shows that displacements in excess of -5µm/+5µm and a response time of less than 300ms are achievable.**

I. INTRODUCTION

Electrothermal actuators are known as being compact, stable and possessing a high force density [1], making them convenient for the development of micro and nanopositioning systems and MEMS devices. The commonly used V-shaped thermal microactuator has the advantage of possessing a high mechanical stiffness which allows it to act with a higher force density, however it is suitable for movement in only one direction and cannot be adopted for bi-directional movement (consisting of positive and negative displacements). Recently it has been shown that bi-directional movement, along one axis, can be achieved using a Z-shaped electrothermal microactuator [2][3].

This paper is motivated by the need to extend the previous Z-shaped electrothermal microactuators to 2-dof (degrees of freedom), and by the integration of sensing elements within the same chip in order to have an integrated MEMS device with actuation and sensing capabilities. A 2-dof electrothermal MEMS nanopositioner has therefore been microfabricated, with this paper reporting its principle of functioning and its full characterization.

The paper is organized as follows. In section-II, we present the principle of functioning and the developed 2-dof MEMS with integrated actuation and sensing capabilities. Section-III is devoted to the characterization of the sensing elements while section-IV is for the characterization of the actuation elements. Finally, we conclude the paper and give some discussions on future works in section-V.

II. DESIGN AND DEVELOPMENT OF THE 2-DOF MEMS

To explain the principle of actuation and sensing of the electrothermal 2-dof MEMS, we consider the simplied structure for one axis as pictured in Fig.1. In this figure, two sets of poly-Si z-shaped beams are connected to the extremities of a movable table. These z-shaped beams will be used for the actuation. Underneath the table, two poly-Si resistors are conveniently placed. These two resistors will be used for the sensing.

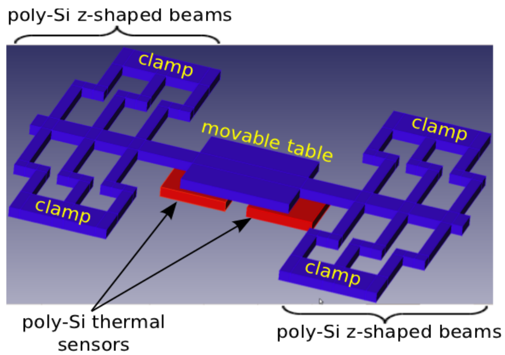

Fig.1. A CAD-scheme showing a simplified structure of the MEMS in one axis.

A. *Principle of the actuation*

To generate a movement of the table, the 2 sets of z-shaped beams are bent. More precisely, when the upper set of z-shaped beams is heated thanks to an electrothermal Poly-Si heater underneath it, it bends. Consequently, the rest of the structure is pulled towards these beams and a movement in one direction is obtained for the movable table (Fig.2b). Alternately, the heating of the lower set of z-shaped beams allows the movement of the table in the opposite direction (Fig.2c).

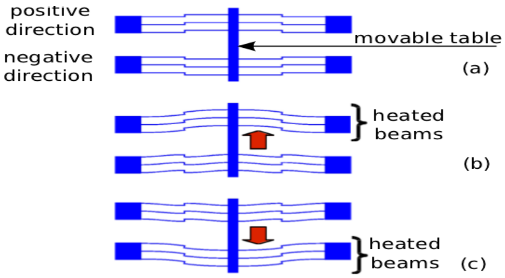

Fig.2. (a): initial state of the z-shaped beams. (b): upper z-shaped beams heated. (c): lower z-shaped beams heated.

B. Principle of the sensing

The sensing is obtained using the two poly-Si resistors placed symmetrically underneath the table. The resistors are electrically supplied during the utilization of the MEMS and then heated by Joule effect. During the movement of the table in one direction, the overlap between it and the resistors is modified and affects the thermal exhange between them (Fig.3). The resistivity of the two resistors are consequently modified in a push-pull way: one resistivity is increased while the another one is decreased. An electrical circuit that amplifies this difference can tehrefore be used to yield a voltage that is an image of the table's displacement (Fig.3).

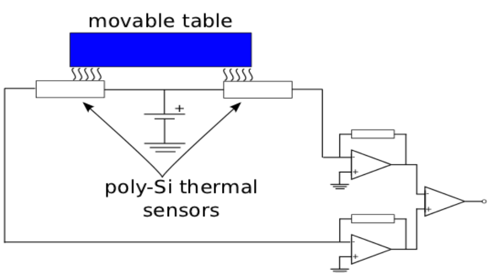

Fig.3. Principle of the sensing elements of the MEMS.

C. The developed 2-dof MEMS

The principle of actuation and sensing presented above was extended into 2-dof. For that, instead of using two sets of z-shaped beams to actuate the table, four sets are used to make possible a bi-directional movement for two axis (x-axis and y-axis). Two additional resistors are also added underneath the table in order to allow the sensing for the two axis. The nanopositioner was fabricated using MEMSCAP's SOIMUMPs SOI micromachining process [4]. Fig.4 pictures a SEM (scanning electron microscopy) image of the developed 2-dof MEMS. Its sizes are comprised in a square of 3mm x 3mm. As we can see from the figure, four linear shaped beams are put in each of the four quadrants. They are used to guide the movement of the table in each axis (x and y) and then to minimize the couplings between them. The section of these quadrants beams were minimized such that the heat transfer from one actuator (set of z-shaped beams) to another actuator (another set of z-shaped beams) is as small as possible.

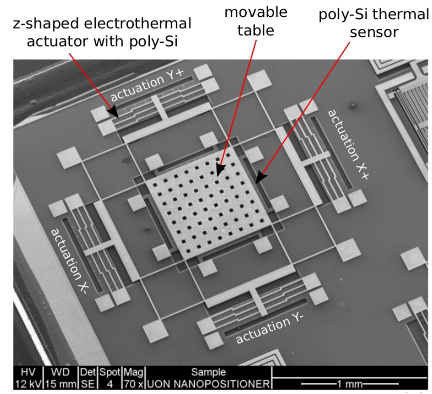

Fig.4. A SEM image of the 2-dof electrothermal MEMS with actuation and sensing capability.

III. CHARACTERIZATION OF THE SENSORS

The aim of this sectio is to evaluate the behavior of the integrated sensors of the MEMS. For that, a micro system analyzer (MSA-500 MEMS analyzer from *polytec*) is used to apply actuation voltages to the MEMS and to measure the real displacement x and y of the movable table. In the meantime, the sensors output voltages; more precisely output of the electrical circuit in see Fig.3; are recorded. Then, the map that relates the sensors output voltages with the real displacement is plotted (Fig.5). From these results, we conclude that the sensors behavior is almost linear for the two axis. Nonetheless, we remark that the gain in the positive direction is different from the gain of the negative direction. This is mainly due to a slight difference between the values at rest and the sensivity of the two push-pull resistors of each axis. Although, this can furthe be compensated by gains that allow to trace back the displacement from the sensors voltages.

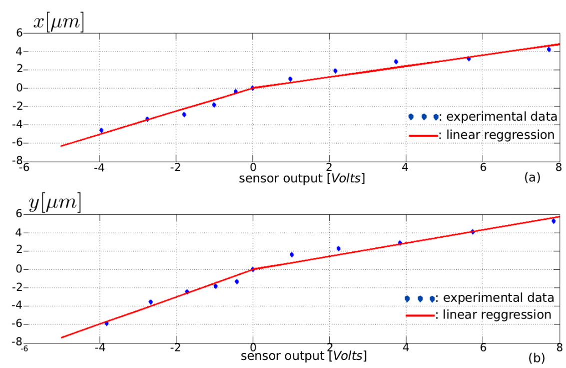

Fig.5. Sensors output voltages versus the displacement of the movable table.

IV. CHARACTERIZATION OF THE WHOLE 2-DOF MEMS

In this section, the whole 2-dof MEMS (actuation and sensing comprised) is characterized. For that, the sensors gains are introduced and hence the output of MEMS is directly the displacement x[µm] and y[µm] while the input is the actuation voltages Ux[V] and Uy[V]. Fig.6 displays an equivalent block diagram of 2-dof MEMS which indicates that the latter can be seen as a 2-inputs-2-outputs system. The characterization will include not only the behavior of each axis but also the coupling between them.

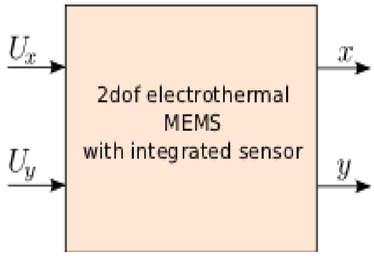

Fig.6. Equivalent block diagram of the 2-dof MEMS.

A. Input-output (static) characteristics

The procedure to characterize the static (or low frequency) behavior is as follows. First, a triangular input voltage Ux is applied. The amplitude of the voltage is chosen to provide a range of displacement x that covers the expected application. The frequency is chosen to be low enough in order to avoid the effects of the dynamics (also called phase-lag) to the resulting characteristics. Amplitude Ux=150V and frequency f=0.05Hz have been chosen as they well satisfy these conditions. The resulting x-displacement is recorded and plotted versus the voltage Ux (see Fig.7a) and the direct transfer on the x-axis is obtained. In the meantime, the influence of Ux to the y-axis is also plotted (Fig7c). This is the coupling on the y-axis. Afterwards, the voltage Ux is set to zero and a similar experiment is performed with a triangular input voltage Uy. The resulting direct transfer Uy → y and the coupling Uy → x are plotted (Fig.7d and Fig.7b respectively). These results show first that the 2-dof MEMS is nonlinear (Fig.7a and d). In fact, these nonlinearities mainly come from the nonlinear phenomena in the resistivity and in the thermal coefficients of the actuators heaters and sensors poly-Si resistors [5]. It is also shown that displacement inexcess of +/-5µm can be achieved. On the other hand, Fig.7b and Fig7c display a slight coupling between the two axes. Finally, the resolution offered by the MEMS is well adapted for nanopositioning applications. Indeed, From Fig.7a and d we can see that it is possible to yield a displacement much better than the micron by applying lower voltage.

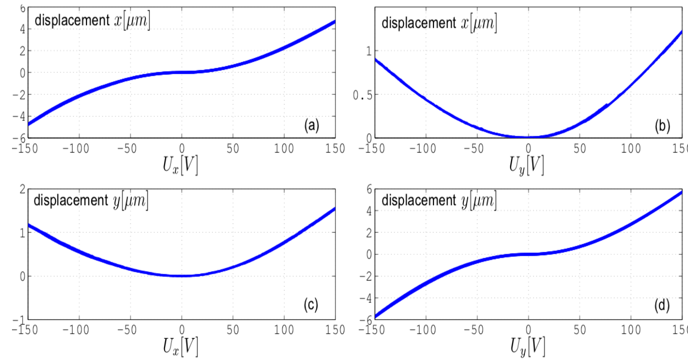

Fig.7. Output displacement (x and y) versus input voltages (Ux and Uy).

B. Step responses

The aim of the step responses characterization is to evaluate the transient part of the response of the MEMS when brusque input voltages are applied. Fig.8a and b give the step response for the x-axis and for the y-axis respectively when different amplitudes of input are used (50V, 100V, 150V). These results demonstrate that the MEMS device has a well damped behavior. Finally, we derive from the figures that a response time of less than 300ms is achievable with the device.

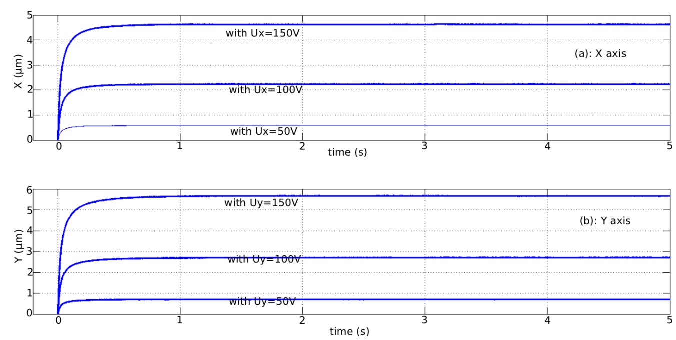

Fig.8. Step responses along x and y axis for different input voltages.

C. Frequency response

The last experiment consists in studying the frequency response of the 2-dof MEMS. Fig9a and Fig.9d display the responses of the direct transfers Ux → x and Uy → y respectively. They show that the bandwidth of the MEMS is nearly 3Hz. Fig.9b and Fig.9c display the couplings Uy → x and Ux → y respectively. Although the existence of couplings, they are low (less than -42dB) relative to the expected direct transfers (about -30dB at low frequency). Then it is easier to further calculate a feedback controller that will reject them and that will improve the dynamics and the accuracy of the 2-dof MEMS.

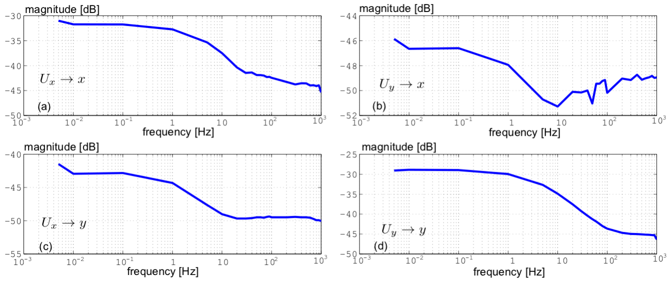

Fig.9 Frequency response of the 2-dof MEMS.

D. Summary of the characteristics

The developed 2-dof MEMS performs a displacement range in excess of +/-5µm for both x and y axis with an operational voltage of +/-150V. The resolution of the displacement is of tens of nanometers and is directly related to the applied voltage (Fig7 and Fig8). However, the static behavior of the 2-dof MEMS is nonlinear. Concerning its dynamics, the device can achieve a settling time less than 300ms and a bandwidth of about 3Hz. Finally, we observe a slight coupling between the two axis which is due to the mechanical design and to a heat transfer from one axis to another one. This coupling can be rejected thanks to a further feedback controller that will employ the senors integrated in the MEMS.

V. Conclusion

This paper presented the presentation and characterization of a 2-dof electrothermal MEMS that integrates a z-shaped actuators and poly-Si sensors. We shown that the MEMS device can achieve a range of displacement more than +/-5µm with a resolution in the order of tens of nanometers which are convenient for nanopositioning applications. Furthermore, the provided response time is less than 300ms and can still be improved thanks to a closed-loop (feedback) controller by using the integrated sensors. Future works will enclude the study and experiments of such closed-loop control technique in order to enhance the performances of the 2-dof MEMS (static, dynamics) and also to reject the couplings between the two axis.

Acknowledgment

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