Multi-axis piezoresistive MEMS force sensor

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***Abstract*— This study presents a new multi-axis friction sensor. This chip is designed to measure normal forces up to 1 mN and friction forces up to 100 µN and will be used to study multi-asperity nanotribology. First prototypes have been manufactured on a p-type Silicon on Insulator wafer (SOI) and characterized.**

I. INTRODUCTION

At the nanoscale and for particular applications such as dexterous micro-manipulation, two Degrees of Freedom nanotribometers are no longer adequate for studying and characterizing the contacts [1, 2]. Indeed, when wear becomes negligible, all the friction components (sliding, rolling, swiveling) are involved in the friction process and have to be detected simultaneously Therefore a new multi-axis friction sensor designed for nanotribological testing applied to this purpose is required in order to extract each contribution independently. Optimization of the fabrication process (ohmic contact achievement) and sensor microfabrication was then performed in clean–room using RENATECH network and its FEMTO-ST technological facility. In order to obtain a compliant structure as perfect as possible a five layers SOI wafer was used. It is composed of a central platform with a fixed ball and surrounded by a compliant table. Its sensing ability is based on piezoresistive properties: four sets of piezoresistors are symmetrically distributed at the root of four central beams. The resonant frequencies and their corresponding mode shapes are simulated by finite element modeling to verify the numerical results. In the sections that follow, we will detail the design, fabrication techniques, modeling and test results, for this multi-axis piezoeresistive MEMS force sensor.

II. SIMULATION

A first study was performed to choose the most adapted design for our application: eight Silicon (100) p-type piezoresistors are placed on a Silicon (111) structure made of a compliant structure formed by several beams and platforms as shown in Figure 1. This compliant table presents advantages compared with classical cross-beam sensors [3]. Moreover the combination of this innovative design with the piezoresistive sensing technology [4] allows to obtain a bulk-multi-axis nanotribometer adapted to our requirements. Optimization of the sensor design (dimensions, gauges type and position) by multiphysics simulations have then been performed using the computing resources from the Mésocentre of Franche-Comté. This study is detailled in [5].

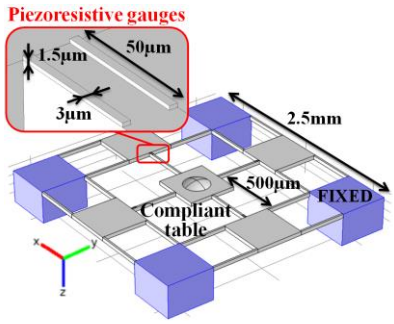

Figure 1. Illusatrion of the he multi-axis piezoresistive MEMS force sensor

Simulation results presented in Table 1 and Figure 2 are promising in terms of sensitivity, lower crosstalk and high enough resonant frequencies to avoid perturbations due to environmental noise (acoustic and seismic vibrations [6]) during the measurement.

Table 1: Simulation results of the sensor optimised.

Sensitivities				Stiffness	
$S_{\widehat{Fx,y}}$ (nA/µN)	$S_{\widehat{Fz}}$ (nA/µN)	$S_{\widehat{Mx,y}}$ (nA/µrad)	$S_{\widehat{Cz}}$ (nA/µrad)	$K_{x,y}$ (kN/m)	K_z (kN/m)
17.3	43.2	12.9	229	4.10	2.31

Maximal forces / displacements before rupture		Crosstalks		Response times	
$F_{x,ymax}$ (mN) / $D_{x,ymax}$ (µm)	F_{zmax} (mN) / D_{zmax} (µm)	$\widehat{Fx,y}/\widehat{My,x}$ (%)	$\widehat{Mx,y}/\widehat{Fy,x}$ (%)	$\tau_{\widehat{Fx,y}}$ (ms)	$\tau_{\widehat{Fz}}$ (ms)
33.5 /8.16	22.9 /9.94	0.713	19.1	1.11	1.40

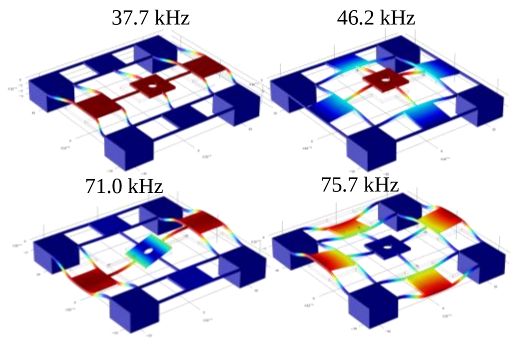

Figure 2. Mode shapes of the piezoresistive sensor simulated by finite element

III. MICROFABRICATION

Bulk micromachining technology was widely used to achieve the membranes production in MEMS and NEMS area [7, 8]. This paper reports on a process using deep reactive ion etching (DRIE) on 5 layers silicon-on-insulator (SOI) wafer to form a high aspect ratio suspending compliant table structure based on multi-axis fingers. The whole final fabrication process is presented in Figure 3 and the obtained prototype in Figure 4.

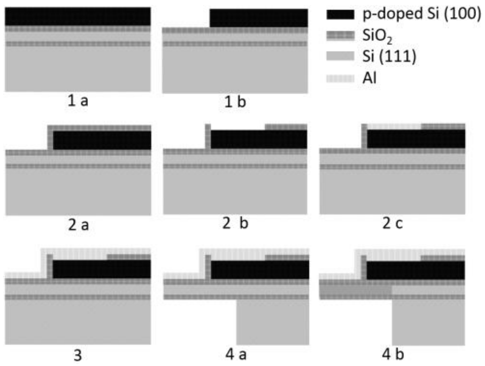

Figure 3. Flow chart: (1 a) (1 b) SOI wafer with 5 layers, gauges achievement (2 a) (2 b) (2 c) Ohmic contacts achievement using RTA process [9] (3) Connection circuit achievement (4 a) (4 b) Multi beam structure achievement.

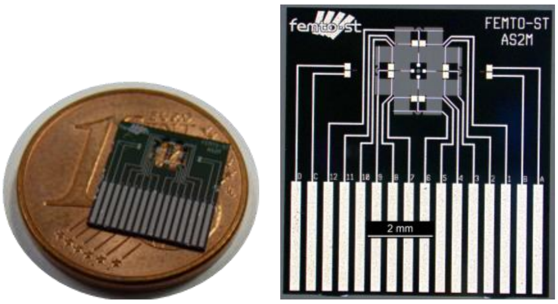

Figure 4. Photography and optical image of the multi-axis sensor

IV. Characterization

To measure the resonance frequencies, the entire chip was placed on a PZT piezoelectric transducer. The dynamic measurement was performed by using an alternative voltage which was applied between the upper and lower metallic electrodes of the piezoelectric transducer to induce a vertical oscillating strain with a frequency that can be controlled and modulated. A laser beam was focalized at the chosen scanning area. These experiments were achieved using a Polytec MSA 500 laser Doppler Vibrometer System. The measured resonances frequencies by this technique measurement (viz. LDV) were carried out by a bandwidth range from 20 kHz to 120 kHz (Figure 5).

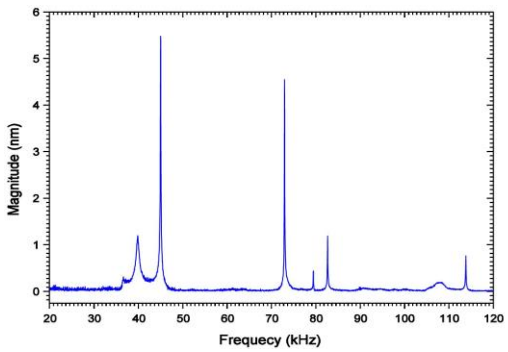

Figure 5. Resonant frequencies responses of sensor membrane (LDV)

Compared to the simulations values, one can note that these results are in relatively good agreement (Figures 2 and 6). This sensor will be able to measure independently the normal and the friction forces (crosstalk inferior to 1%) with a good sensitivity.

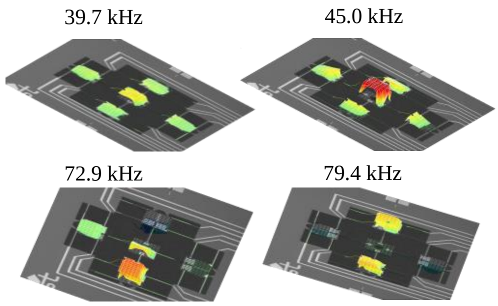

Figure 6. Mode shapes of the piezoresistive sensor measured by LDV.

V. Conclusion

A Multi-axis piezoresistive MEMS force sensor intended for applications in material science, biological research, and Microsystems characterization was presented. 3D-FEM analysis was performed in order to find the best materials and crystallographic orientations and the optimal dimensions for the sensor and its expected characteristics. These forces sensors were designed and validated together by comparing to measured resonance frequency and the ones obtained by finite element simulation. This device force sensor has been successfully designed and fabricated.

Acknowledgment

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