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Linearity of Piezoresistive Nano-Gauges for MEMS Sensors

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Abstract

The work discusses the mechanical properties and the response linearity of sub-micrometric crystalline Silicon beams used as piezoresistive sensing elements (nano-gauges) in MEMS sensors. The study is based on a suitably developed test structure that allows applying bidirectional stresses to a gauge with a cross-section of (250 nm)^2, and to monitor the displacement both through a reference linear capacitive sensor and through the nano-gauge piezoresistive variation.

Experimental measurements estimate a nominal strength of 6.6 GPa, and a linear range of 2.3 GPa and 1.1 GPa under tensile and compressive stresses respectively, the latter value being limited by buckling effects.

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Keywords: crystalline Silicon; NEMS; surface micromachining; piezoresistive effect.

1. Introduction

Piezoresistive sensing through sub-micrometric Silicon beams was demonstrated as a possible alternative to parallel-plate sensing capacitors in microelectromechanical systems (MEMS) [1]. Among the advantages of this approach are the sensing elements miniaturization, the absence of pull-in issues, the minimization of squeeze-film damping typical of parallel plates, and possible aggressive on-off duty cycles of the readout circuit to reduce power consumption for low-power applications. Preliminary operation of various sensors (accelerometers, gyroscopes, pressure sensors) based on this technology, with a nano-gauge cross-section in the order of (250 nm)^2, was demonstrated in previous works [1, 2]. A detailed study of the linearity characteristics of the nano-gauge piezoresistive coefficient was however not shown.

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In order to optimize the sensors design, and, in particular, in order to make the nano-gauge linear range match the target full-scale of the quantity to sense, it is relevant to know the linearity limits of the piezoresistive sensing elements. This work addresses this goal through a suitably designed structure that allows measuring both the gauge nominal strength and its piezoresistive response linearity. The maximum stress in tension and compression which correspond to the 5% linear range is in this way identified.

2. Description of the test structure

Fig. 1a shows the schematic working principle of the designed device: the structure is formed by a rectangular frame, suspended through six springs and through a lever designed at one end, which includes a hinge-gauge rotational constraint. Suitable comb fingers, branching from the suspended frame, form a bidirectional electrostatic actuator, which can deliver forces large enough to lead the gauge to single-cycle failure. Another set of comb fingers forms an electrostatic capacitive sensor, representing the linear reference for displacement measurements.

During an electrostatic actuation, the lever (Fig. 1b) transfers the force to the 5-µm-long gauge (Fig. 1c), in a configuration similar to those used in inertial sensors [2]. Fig. 2 is an optical microscope top-view picture of the device, showing the details of the lever system: movements of the suspended frame towards the bottom of the figure generate compressive stresses on the gauge and determine an increase of the sensing capacitance. The opposite situation occurs when the suspended mass is displaced towards the top of the image.

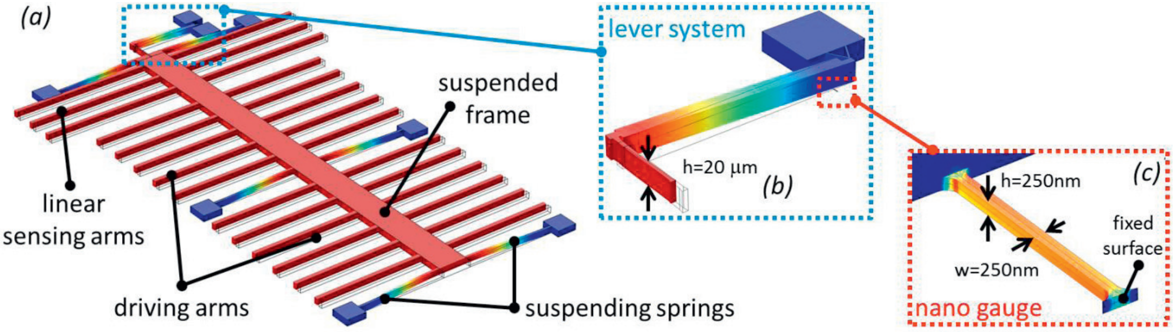

Fig. 1: working principle of the device presented in this work: (a) a set of electrostatic electrodes is used to apply a force to a rectangular frame; through a lever system (b), the force is transferred to a piezoresistive nano-gauge (c). The displacement can be monitored through a reference (linear) capacitive sensor and can be compared to the gauge resistance change to infer the linearity of the sub-micrometric piezoresistive element. The fingers of the electrostatic sensors/actuators are not shown for sake of simplicity.

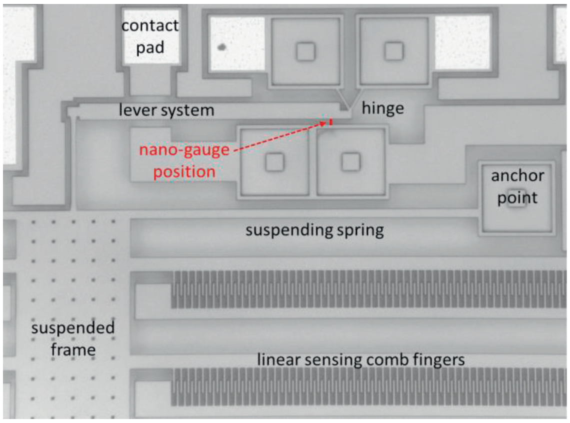

Fig. 2: optical microscope image of the device, representing a close-up view of the lever system. The nano-gauge position is indicated in red and marked by the arrow. The suspended mass height is 20 µm, the nano-gauge length is 5 µm and the nano-gauge cross-section is (250 nm)^2. The gap between the sensing fingers is 1.5 µm.

3. Readout electronics and nominal strength evaluation

One single, versatile, low-noise electronic setup is used to measure the displacement through either the reference sensing capacitance or the piezoresistive elements. The readout is based on a 1-MHz modulated test signal. The two configurations share both the front-end (Fig. 3a and 3b) and some conditioning, filtering and demodulating stages as shown in Fig. 3c. Further details of the electronics can be found in [3, 4].

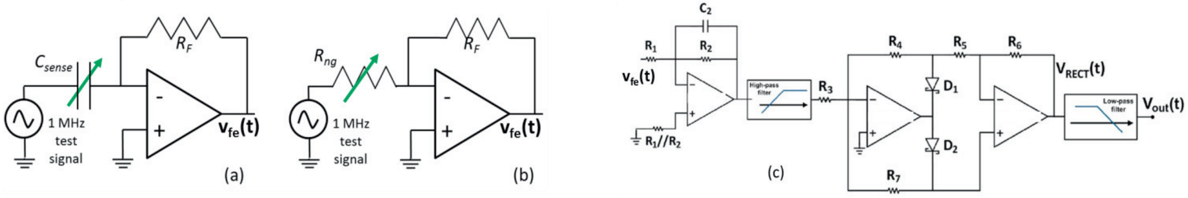

Fig. 3: simplified front-end of the electronics used (a) in capacitive mode and (b) in piezoresistive mode. In (c) further amplifying, rectifying and filtering stages are shown, used to demodulate the 1-MHz test signal applied to the front-end.

The first part of the experimental campaign consists in the nominal strength evaluation, obtained by leading 10 structures to single-cycle failure under tensile stress (a similar procedure was used e.g. in [3]). A rising voltage is applied to the driving electrode and the capacitance variation (linear with the displacement, so parabolic with the applied voltage) is measured: when the stress on the nano-gauge overcomes the failure limit, a sudden change in the curve occurs, well visible in the measurements of Fig. 4. This sudden change is due to the missing stiffness contribution from the broken nano-gauge. For comparative purposes, the results of the capacitance variation obtained from finite element (FEM) simulations predictions is also shown. From the found average failure voltage (around 52 V), and through the comparison with FEM, a 6.6 GPa nominal strength is estimated.

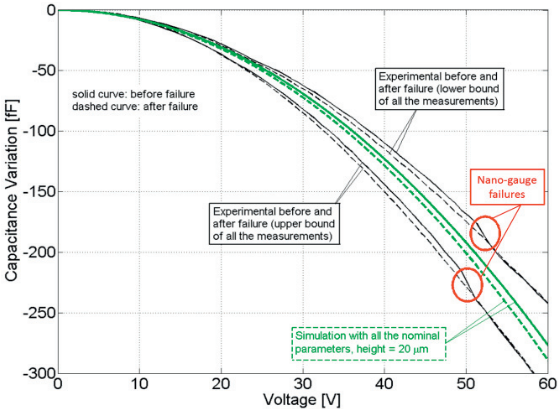

Fig. 4: capacitance-to-voltage curve before and after the nano-gauge failure. FEM simulations are compared to upper and lower-bound experimental measurements (all other devices lie within these curves). The red circles highlight the gauge failure.

4. Linearity measurements and conclusions

In the second part of the experimental campaign, the gauges are characterized with both tensile and compressive stresses, increasing by quasi-stationary small steps from 0 V to a value well below the failure voltage found above. Fig. 5 compares the displacements measured under the actuation force through the linear electrostatic capacitor and the nano-gauge piezoresistor, for both the driving directions. The results demonstrate a large linear range for tensile stresses (linearity errors below 5% up to 2.3 GPa), and a lower linear range for compressive stresses (1.1 GPa). This behavior can be explained by recalling the expression of the buckling stress [5] for a bar having a length L , built in a material having a Young modulus E =169 GPa, and having either a square cross-section with a side b, or a circular cross-section with a radius r:

$$\sigma_{b,square} = \frac{\pi^2 \cdot E \cdot b^2}{3L^2} = 1.39\ GPa \qquad \sigma_{b,circ} = \frac{\pi^2 \cdot E \cdot r^2}{L^2} = 1.04\ GPa\ .$$

These formulas are ideally valid for a stress which is parallel to the bar axis. Though the rotation of the hinge around its center, this approximation still holds in this case, as the applied force on the nano-gauge is almost orthogonal to the lever system. One can note that the measured linearity limit in compression (Fig. 5) is within the range described by the formulas above. Considering that the nano-gauge is not an ideal parallelepiped, due to edges smoothing occurring during fabrication, one can conclude that buckling is the limiting phenomenon for the linearity of such a structure when actuated by compressive stresses. In the specific case of the designed structure, buckling is non-destructive because the structure stiffness is determined mostly by the suspending springs, as shown in Fig. 4. On the other side, for tensile stresses, the limiting factor is represented by the nonlinearity of the piezoresistive coefficient.

The results of the analyses of this work will be exploited in the future for the optimization of the design of 9-axis sensors based on piezoresistive Silicon nano-gauges.

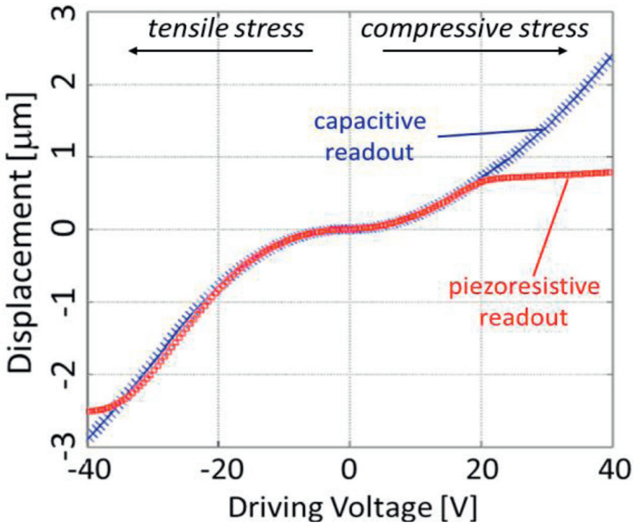

Fig. 5: measured displacement under electrostatic forces applied by the actuator. The cross-marker curve is the response of the capacitive sensor; the circle-marker curve is the nano-gauge piezoresistive response. Buckling is well visible in compression.

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