AUTO-CALIBRATED CAPACITIVE MEMS ACCELEROMETER

L.A. Rocha[1], L. Mol[2], E. Cretu[3], R.F. Wolffenbuttel[2] and J. Machado da Silva[1]

[1]Dept. of Electrical and Computer Eng., Fac. of Eng. of the U. of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

[2]Dept. Microelectronics, Fac. EEMCS, Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands

[3]U. of British Columbia, Dept. Electrical and Computer Eng., 2332 Main Mall, Vancouver, BC, V6T 1Z4 Canada

Abstract — *An electronic calibration technique for capacitive MEMS accelerometers based on the measurement of pull-in voltages is described. A combination of pull-in voltages and resonance frequency measurements can be used for the estimation of process-induced variations in device dimensions from layout and deviations in material properties from nominal value, which enables auto-calibration. Measurements on fabricated devices confirm the validity of the proposed technique and electronic calibration is experimentally demonstrated.*

Key Words: *MEMS accelerometers, pull-in, calibration*

I. INTRODUCTION

Accelerometers and pressure sensors are products based on microelectromechanical systems (MEMS) technology with a high commercial success and impact [1]. Several accelerometer designs are commercially available, from simple single axis to more complex three axes devices. Despite the evolution of acceleration microsensors in the last 30 years, MEMS based accelerometers need to be calibrated for use in high performance applications.

Accelerometer calibration is usually done by measuring the response of the sensor to a sequence of +1g followed by -1g static acceleration test signals; this is accomplished by aligning the sensitive axis parallel with the gravitational field, and switching between the two possible orientations. This calibration step is often done manually, and is therefore an inconvenient alternative for remotely placed sensors or for sensors difficult to access. Auto-calibration capabilities would be preferred instead, since they allow the inertial sensors to be integrated in autonomous self-calibrated systems.

This paper introduces an electronic calibration technique for capacitive MEMS accelerometers based on the measurement of pull-in voltages. Pull-in [2] is a unique feature of gap-varying capacitive MEMS devices, and can provide detailed information about their characteristics. Since the attractive force due to an electrostatic field is inversely proportional to the square of the deflection, while the restoring elastic force is (to a first approximation) linear with deflection, an unstable system results in case of a deflection, v, beyond a critical value, v_{crit}. The **pull-in voltage**, V_{pi}, is defined as the voltage that is required to obtain this critical deflection and depends mainly on geometry, residual stress level and material properties. This dependence makes it ideal for characterizing structural materials in surface micromachining processes [3,4]. Unlike the case of the comb drive, which is based on area-varying capacitors, the design of most electrostatic actuators relies on gap-width varying capacitors and the pull-in phenomenon has to be considered [5]. Pull-in causes the displacement range due to electrostatic force to be limited to 1/3 of the gap between the electrodes, in case of a motion of the movable capacitor plate perpendicular to the plates.

When pull-in voltage measurements are combined with the measurement of the resonance frequency (a single measurement is needed), fabrication process non-idealities like over-etching and process asymmetries can be accurately estimated [6]. The parameters of an accurate device model could be extracted from this measurement setup, providing in fact an equivalent calibration capability as the application of an external inertial force of ±1g, but using only electronic excitation.

II. PULL-IN VOLTAGE AND NON-IDEALITIES ESTIMATION

The simplest symmetric micromechanical system suitable for studying the pull-in voltage is composed of three electrodes. Two of them have a fixed position on the rigid supporting substrate, while the middle one is movable and connected to an elastic suspension with the spring constant k (Fig. 1a). This is often the case of capacitive accelerometers with separate electrodes for sensing and actuation. The static balance between the elastic and electrostatic forces defines the equilibrium position of the movable plate for a given actuation voltage. Its stability is given by the rate of variations of the two forces for small perturbations around the equilibrium point, that is, by the second derivative of the global potential energy. For a stable equilibrium, the second derivative of the potential energy of the system with respect to deflection should be positive: $\partial^2 U_p / \partial x^2 > 0$; thus the pull-in voltage (V_{pi}) results as the solution of the two equations corresponding to $\partial U_p / \partial x = 0$ (force equilibrium) and $\partial^2 U_p / \partial x^2 = 0$ (margin of stability). Pull-in voltage is determined by the elastic flexure (beam) material and dimensions, residual stress, and the geometry of the electrodes. The beam should be suspended using folded tethers at each end, in order for the residual stress to not affect V_{pi}[7]. This approach ensures that the built-in strain energy component caused by longitudinal stress is negligible. The geometry of the structure allows the definition of two pull-in voltages, as shown in Fig. 1a: asymmetric-right (V_{pr}), and asymmetric-left (V_{pl}). They will be equal in ideal conditions (perfectly symmetric structure), as can be shown by the theoretical analysis [2]:

$$V_{pr} = V_{pl} = \sqrt{\frac{8}{27}\frac{d_0^3 k}{\varepsilon_0 w l}}\,, \tag{1}$$

Here d_0 is the capacitor initial gap, k is the mechanical spring constant, ε_0=8.8546x10^{-12} is the air permittivity and *w* and *l* are the capacitor plate width and length, respectively.

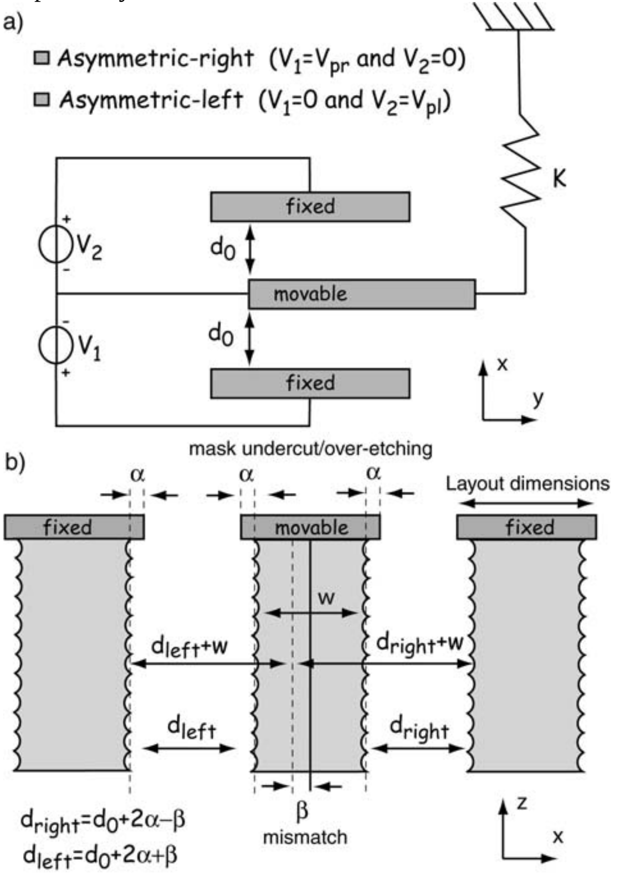


Figure 1. Sketch of the basic device with a) ideal conditions and b) with over-etch and asymmetries

If non-ideal process conditions are now considered (Fig. 1b) like over-etching [8], capacitor gap mismatch and Young's Modulus (*E*) value deviations, the pull-in voltage values will vary. They become suitable, easy to perform measurements (with simple electronics) for estimating technological and other non-idealities and for use as diagnostic mechanism.

The method proposed in [6] uses the pull-in voltage as a test mechanism for microelectromechanical systems, for instance to identify process-induced variations in the real device geometry. Fabricated devices often exhibit actual dimensions smaller than the designed on the mask layout (due to over-etching). Over-etching can be considered uniform at the scale of one microfabricated device [8], which means that all layout dimensions will be affected by the same parameter α. This will have a uniform effect on both pull-in voltages. Besides over-etching effects, small gap mismatches (a few nm in misalignment) are also observed in fabricated devices. As the gap mismatch (β) will affect differently the pull-in voltages, it becomes easy to estimate β from the differences between V_{pl} and V_{pr}. The parameter α is more difficult to estimate, because there is an extra unknown parameter: the Young's Modulus (its average value is known, but it can show large deviations). If we introduce a new measurement, the resonance frequency, both α and *E* can now be estimated and the uncertain parameters of the mechanical device are identified. Therefore, as the sensitivity of the device is known, test signals can now be applied to the actuation capacitors to calibrate the full system (device plus readout electronics).

One disadvantage of the proposed technique is that it relies on using accurate device models to predict the device electro-mechanical behavior. These models have to incorporate all the non-idealities existing in the micro-domain, like capacitor fringe fields and residual stress, which makes the modeling one of the critical parts of the proposed calibration method.

III. EXPERIMENTAL RESULTS

Accelerometers fabricated using Bosch epi-poly technological process[9] were used to evaluate the auto-calibration method. A simplified drawing of the devices used is depicted in Fig. 2.

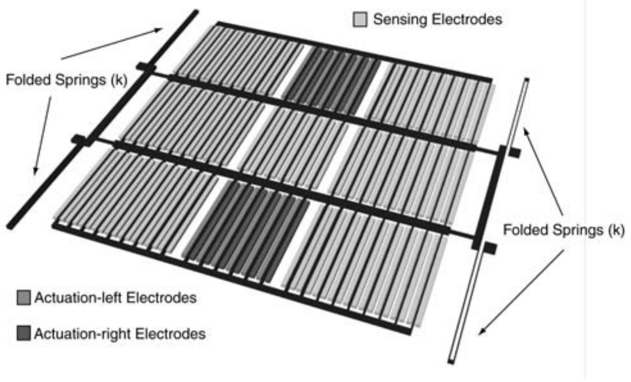


Figure 2. Drawing of the accelerometer

III.1 FABRICATED ACCELEROMETERS

The fabricated accelerometers (Fig. 3.) are composed of four folded springs, 340 μm long and 3 μm wide (layout dimensions), connected to two rigid central bars of about 1mm long. Parallel-plate capacitors with a 2 μm gap are used for actuation. The displacement measurement involves sensing the changes of various sets of differential capacitors. The main device layout parameters and bulk material properties are shown in Table 1.

Table 1. Main nominal parameters of the device (layout dimensions and bulk material mean values)

Parameter	Value
Spring length (*l*)	340 μm
Spring width (*b*)	3 μm
Mechanical layer thickness (*h*)	10.6 μm
Capacitor length (*l*)	282 μm
Capacitor width (*w*)	10.6 μm
Capacitor gap (*d*)	2 μm
Young's Modulus (*E*)	163 GPa (Poly-Si)
Density (ρ)	2.5 g cm^{-3}

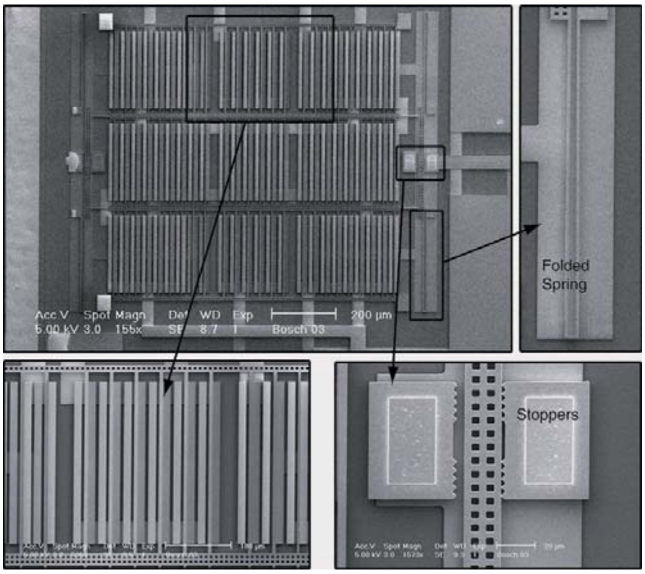


Figure 3. Fabricated device

III.2 ACCELEROMETER ESTIMATED MODEL

A MEMS capacitive accelerometer is a second order mechanical system and can be described mathematically in Laplace complex domain by:

$$\frac{x(s)}{a(s)}=\frac{1}{s^2+\frac{b}{m}s+\frac{k}{m}} \qquad (2)$$

where x is the displacement of the proof mass, a is the external acceleration, b is the damping coefficient, k is the mechanical spring constant and m is the mass of the proof mass. The mechanical system has a resonance frequency given by $\omega_n=\sqrt{k/m}$, and the (DC) sensitivity $S=m/k$.

For a typical calibration procedure the mechanical spring constant and the mass of the accelerometer are the parameters of interest, while the dynamic behavior is less important (calibration is mainly performed in static mode, such that it needs only simple electronic circuits). Using the method described in [6], pull-in and resonance frequency measurements were performed on a fabricated accelerometer, and the estimated model parameters are shown in Table 2.

As the dynamic behavior can be neglected in static equilibrium, the balance of forces on the accelerometer can be written as:

$$k\cdot x=F_{elect}(V)+m\cdot a_{ext} \qquad (3)$$

where $F_{elect}(V)$ is the electrostatic force applied to the movable structure for a given voltage. Equation 3 shows that there are two alternative ways to achieve a certain displacement x: by controlling the applied voltage, while maintaining a zero external acceleration or by applying an external acceleration with no voltage applied.

According to the estimated structure parameters, the fabricated accelerometer has a sensitivity of $S=3.3702\times10^{-9}\,Kg/(N\cdot m)$. An acceleration of ±1g will generate therefore a displacement of ±33nm.

Similarly, if one uses the estimated accelerometer model, the voltage necessary to achieve a displacement of ±33nm can be computed. Considering that a positive displacement occurs when a voltage is applied to the left electrode and a negative one, for a right electrode actuation, the following voltages levels are found:

$$\begin{aligned} V_{+1g} &= 1.14\text{V} \\ V_{-1\text{g}} &= 1.11\text{V} \end{aligned} \qquad (4)$$

Table 2. Measurements and estimated accelerometer parameters using a pull-in based test method [6]

Measurements	**Value**
Pull-In voltage left (V_{pl})	3.942 V
Pull-In voltage right (V_{pr})	3.788 V
Resonance frequency	2740 Hz
Estimated technological parameters	**Value**
Over-etching (α)	255 nm
Mismatch (β)	34.5 nm
Young's Modulus (E)	147.8 GPa
Estimated accelerometer parameters	**Value**
Capacitor gap rigth ($d_{right}=d+2\alpha-\beta$)	2475.5 nm
Capacitor gap left ($d_{leftt}=d+2\alpha+\beta$)	2544.5 nm
Mass (m)	3.978 µg
Mechanical spring (k)	1.18 N.m

III.3 EXPERIMENTAL RESULTS

Two different experiments were made in order to experimentally check the proposed calibration method. The response of the accelerometer to a ±1g external acceleration was firstly recorded. The measured output voltage is shown in Fig. 4.

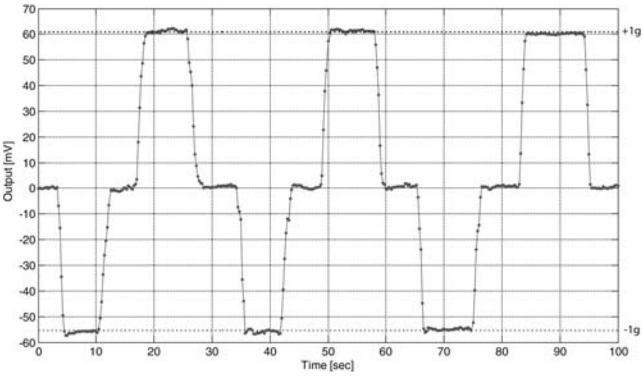


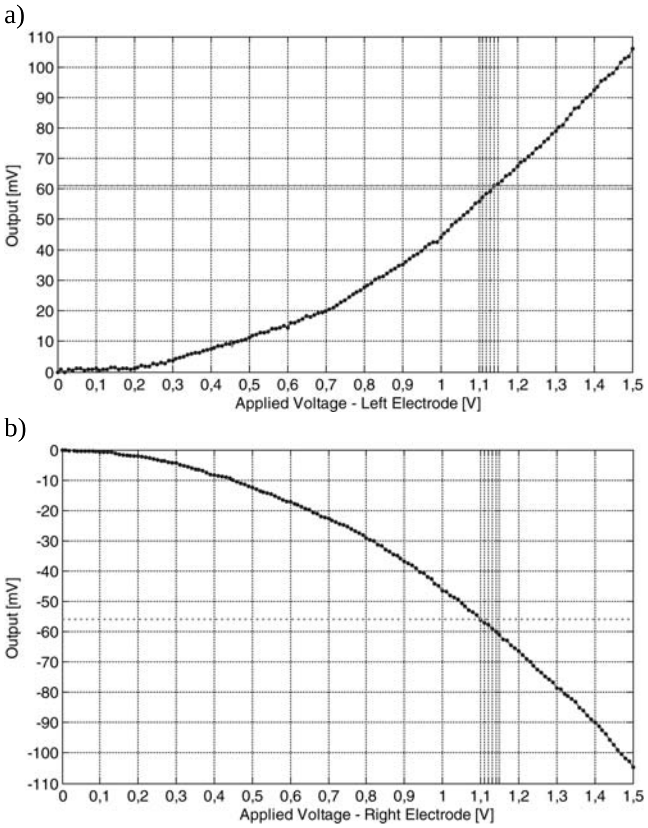
Figure 4. Response to a ±1g external acceleration

Subsequently, the accelerometer response to an increasing voltage on the electrodes, in the absence of an external acceleration, was verified. The measured results are presented in Fig.5.

III.4 DISCUSSION

The results presented in Figures 4 and 5 are very promising and clearly indicate that electric calibration is feasible in capacitive accelerometers. In fact, the results show that the output voltage to +1g external acceleration is equivalent to the response when a voltage of 1.14V is applied to the right electrode (61mV output voltage), while the response to an actuation voltage of 1.11V on the left electrode corresponds to output voltage for an applied external acceleration of -1g.

These results also prove that the estimated model offers a good description of the real behavior of the accelerometer. To further verify model validity, extra measurements were performed: left and right pull-in voltages were measured in the presence of a ±1g external acceleration and compared with the pull-in voltages given by the models for this situation. Since a ±1g generate a displacement of ±33nm, this can be modeled as a new β (mismatch). Therefore, a +1g gives a β of 67.5nm and a -1g gives a β of 1.5nm. The experimental and computed results are shown in Table 3.


a)

b)

Figure 5. Response to an applied voltage in a)left electrode and b) right electrode.

Table 3. Comparative values between measured and estimated pull-in voltages for different external accelerations

		Measured values	Computed values
0g	Pull-In voltage left	3.942 V	3.943 V
	Pull-In voltage right	3.788 V	3.786 V
+1g	Pull-In voltage left	4.019 V	4.018 V
	Pull-In voltage right	3.712 V	3.712 V
-1g	Pull-In voltage left	3.867 V	3.868 V
	Pull-In voltage right	3.862 V	3.861 V

The very good agreement between measured and computed values using the estimated model validates again the calibration approach.

IV. CONCLUSIONS AND FUTURE WORK

A pull-in based solution for MEMS capacitive accelerometer auto-calibration was presented. The technique was validated through experimental measurements and their comparison with the theoretical models.

Experimental results showed that the response to a ±1g external acceleration can be replaced by an equivalent asymmetric actuation voltage, approach that allows a pure electronic calibration of the sensor. The technique can be used in capacitive inertial sensors (e.g. accelerometers and angular rate sensors) and allows their integration in autonomous self-calibrated systems.

REFERENCES

[1] S.D. Senturia, "Perspective on MEMS Past and Future: The Tortuous Pathway from Bright Ideas to Real Products, Proceedings Tranducers'03, pp.10-15, 2003

[2] L.A. Rocha, E. Cretu and R.F. Wolffenbuttel, "Analysis and Analytical Modeling of Static Pull-In with Application to MEMS-Based Voltage Reference and Process Monitoring", J. Microelectromech. Syst., vol. 13,pp. 342-354, 2004.

[3] S. T. Cho, K. Najafi, and K. D. Wise, "Internal stress compensation and scaling in ultra-sensitive silicon pressure sensors," IEE Tr. ED, vol. 39, pp. 836–842, 1992.

[4] P. M. Osterberg and S. D. Senturia, "M-TEST: a test chip for MEMS material property measurement using electrostatically actuated test structures," J. Microelectromech. Syst., vol. 6, pp. 107–118, 1997.

[5] H. A. C. Tilmans and R. Legtenberg, "Electrostatically driven vacuum encapsulated polysilicon resonators, part 2, theory and performance," Sens. Actuators, vol. A45, pp. 67–84, 1994.

[6] L. A. Rocha, L. Mol, E. Cretu, R. F. Wolffenbuttel, J. Machado da Silva and J.S. Matos, "A Test Mechanism for Device Diagnostics and Process Characterization", in Proceedings DCIS'07, pp. 597-602, 2007

[7] W. C. Tang, T.-C. H. Nguyen, and R. T. Howe, "Laterally driven polysilicon microstructures," Sens. Actuators, vol. A20, pp. 25–32, 1990.

[8] J.V. Clark, D. Garmire, M. Last, J. Demmel and S. Govindjee, "Practical Techniques for Measuring MEMS Properties", Proceedings Nanotech 2004, vol. 1, pp. 402-405, 2004.

[9] http://www.bosch-sensortec.com.