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# Compensation of temperature effects on the pull-in voltage of microstructures

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## Abstract

The pull-in voltage of a suspended microstructure has been investigated for use as on-chip voltage reference in a compatible MEMS-IC process. Pull-in is detected using capacitive displacement measurement. The stability is affected by an initial parasitic charge build-up and a temperature sensitivity of $-149\ \mu V/K$. A burn-in procedure is required to minimize the first effect. The temperature coefficient is compensated for by applying additional temperature dependent electrostatic energy to the microstructure. Devices fabricated in an epi-poly process and designed for a nominal pull-in voltage at 5 V have a measured value at 4.7424 V. Drift becomes negligible after 120 h of operation. The temperature reproducibility is within the resolution of the readout at 100 μV over a temperature range between 20 and 60 °C.

*Keywords:* Microelectromechanical systems; Pull-in voltage; Temperature compensation

## 1. Introduction

The inherent instability associated with electrostatic MEMS devices is an extensively studied phenomenon [1,6]. In the quasi-static regime, the model describing the displacement of a MEMS structure in the direction normal to the electrode area, due to the voltage applied, reduces to finding the equilibrium between mechanical and electrostatic forces (the damping is neglected). This results in a sudden pull-in at a well-defined pull-in voltage at 1/3 of the gap for 1DOF displacement structures [3].

As the pull-in voltage depends basically on dimensions, residual stress level and design, it has been used to characterise structural materials in surface micromachining processes [1,2]. Unlike the case of the comb drive, where an electrostatic displacement is associated with a change in area overlap in the capacitor electrodes, the design of electrostatic actuators relying on gap varying capacitors have to consider the pull-in phenomenon [3]. This effect also limits the dynamic range of capacitive accelerometers operating in the feedback mode. Charge drive (current drive with a series capacitance), rather than direct voltage drive can be used to circumvent pull-in, however, at the expense of maximum force at given device dimensions [4]. The use of the pull-in voltage as a voltage reference has also been proposed [5,6], either as on-chip reference or as a transfer standard for metrology. The good mechanical properties of silicon and the stability of its crystalline structure [7] suggest that a reference based on the pull-in voltage should be feasible.

For stable operation as a dc reference, residual stress should not compromise long-term stability. This is the case for a single-ended clamped beam or a structure with folded suspension. Even with this precautions, two main effects affect the long-term stability of a dc reference based on the pull-in of microstructures: parasitic charge build-up at the insulator layers on top of the actuation electrodes [8,9], and a temperature coefficient due to thermal expansion and thermal dependence of the Young's Modulus of the material used [9]. Fig. 1 clearly identifies both effects. These first measurements were performed in a single-sided clamped beam [9,10]. Although not essential for the effect, it should be noted that a structure different in concept and operation was used as compared to the one presented here. In the first 150 h the charge effect is clearly visible. The pull-in voltage shifts from its original value due to trapped charges in the insulator layers on top of the capacitor electrodes. After that period, the imposed temperature (forced by an external heating system) changes the pull-in voltage (see zoom-ins in Fig. 1).

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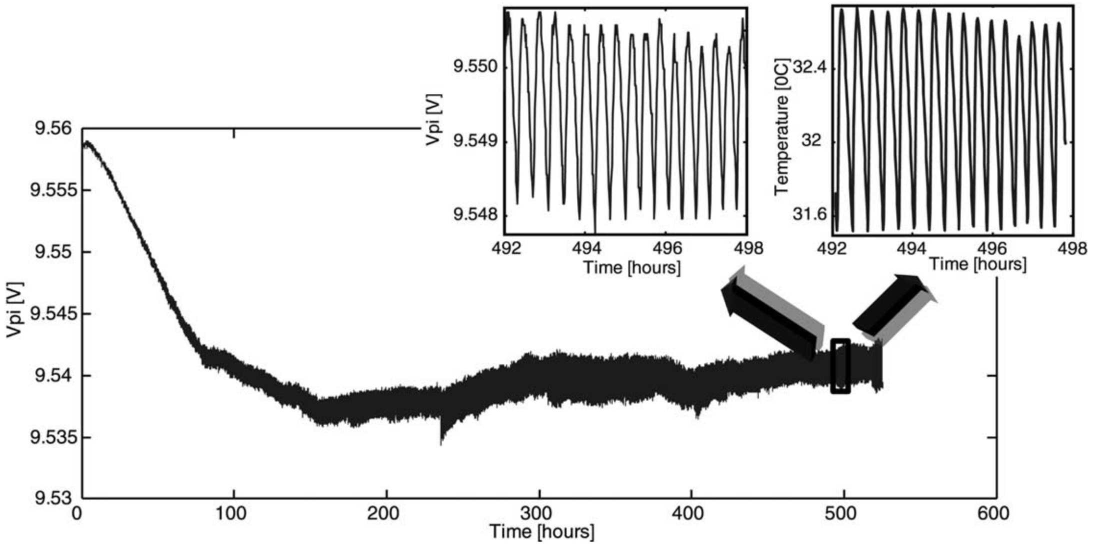

Fig. 1. Identification of the sources of non-reproducibility of pull-in. The effect of charge build-up shows from the global plot and the sensitivity to temperature variations shows from the inserts.

The work reported here, focuses on the second source of uncertainty (temperature coefficient) and a simple and efficient way to reduce the temperature coefficient of the dc voltage reference is presented.

## 2. Device operation and fabrication

The structure used in this work, was fabricated in an epi-poly process [11,12]. This process is very suitable for the fabrication of relatively thick and high aspect ratio free-standing beams on top of a silicon wafer. Epitaxial growth at about 700 nm/min. is used to yield polysilicon layers on top of a dielectric layer with a thickness of 10.6 μm. After deposition the thick polysilicon layer can be patterned using deep reactive ion etching (DRIE). Microstructures can subsequently be released by selectively etching the underlying dielectric sacrificial layer using the DRIE holes as access channel.

The structure used (Figs. 2 and 3), consists of four-folded beams 375 mm long and 2.8 mm wide connected to a central rigid bar of about 1 mm length. The device is actuated using a set of parallel plate comb drive actuators extending from the central bar. The measurement of the displacement is done by sensing the change in capacitance on two sets of sensing capacitors. Stoppers located on the sides of the rigid bar stop the movement after pull-in is reached. The set of actuators are divided in two types of electrodes: (a) actuation electrodes periodically driven to pull-in and (b) compensation electrodes for temperature compensation.

## 3. Pull-in analysis

In a microelectromechanical device with parallel plate actuators, the electrostatic force is inversely proportional to the square of the deflection and the restoring force of the beam is, in a first approximation, linear with deflection. Consequently, there is a critical deflection, $\nu_{\mathrm{crit}}$, beyond which the system becomes unstable. The pull-in voltage, $V_{\mathrm{pi}}$, is defined as the voltage that is required to obtain this critical deflection. For a stable equilibrium deflection the second derivative of the potential energy of the system to deflection should be positive: $\partial^2 U_{\mathrm{p}}/\partial\nu^2 > 0$, thus, $V_{\mathrm{pi}}$ results from $\partial^2 U_{\mathrm{p}}/\partial\nu^2 = 0$.

For a 1DOF structure as the one used, the pull-in is expressed as:

$$V_{\mathrm{pi}} = \sqrt{\frac{8}{27}}d\sqrt{\frac{k}{C_0}}, \tag{1}$$

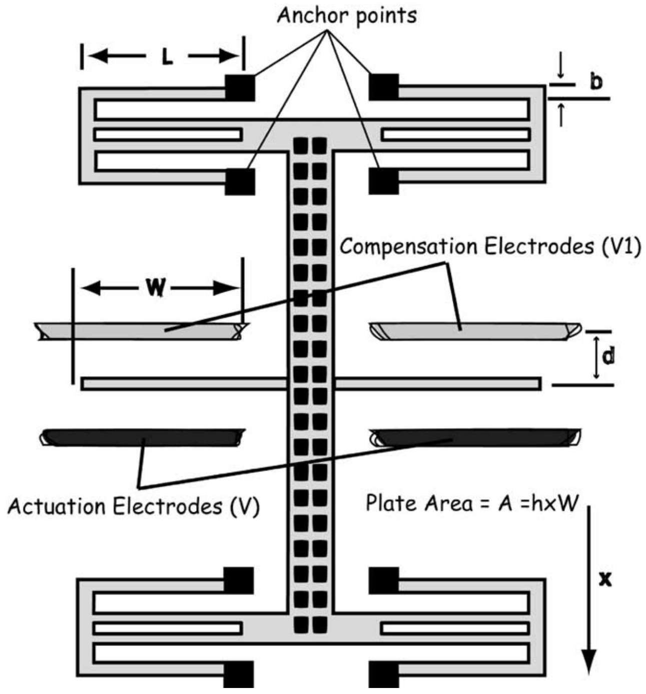

Fig. 2. Schematic of the microstructure used.

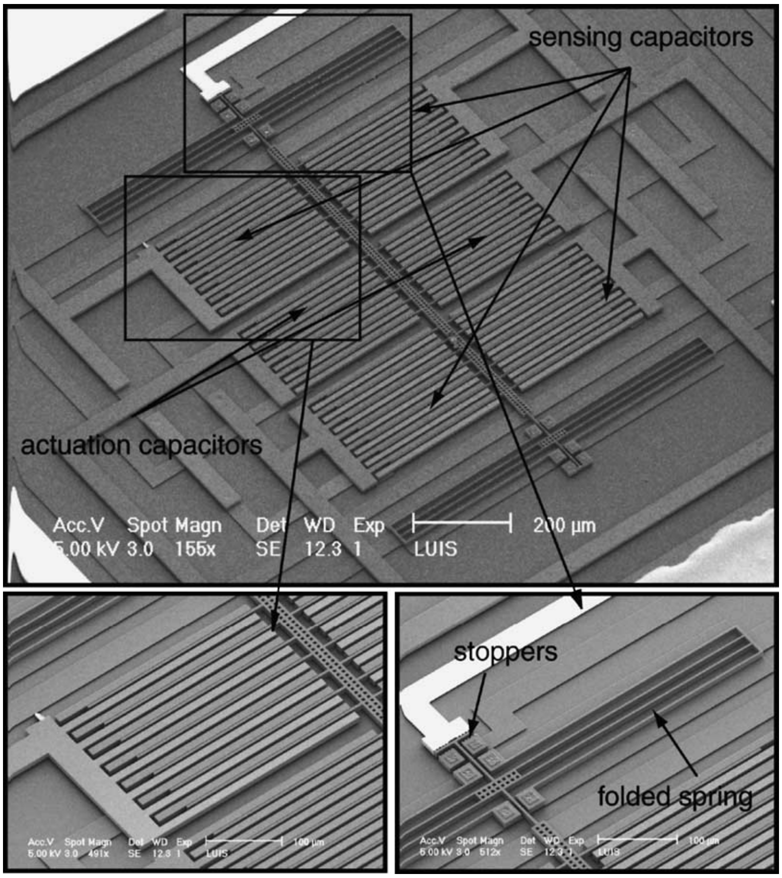

Fig. 3. Photograph of microfabricated device.

where $d$ is the initial gap distance, $C_0$, the initial capacitance and $k = 4Eh(b/L)^3$ is the spring constant ($E$, $h$, $b$ and $L$ are the Young's Modulus, thickness, width and length, respectively).

The polysilicon structure has a thermal expansion coefficient $\alpha = 3 \times 10^{-6}\,\mathrm{K}^{-1}$ and a Young's Modulus thermal coefficient $\beta = -67 \times 10^{-6}\,\mathrm{K}^{-1}$ [13].

If a simple analysis is performed concerning the thermal effects on the structure, in which the effect of thermal expansion on $C_0$ is disregarded, than $k$ remains as the temperature dependent part and can be expressed as $k(T) = k(1 + (\alpha + \beta)T)$ (not considering quadratic terms). Introducing this temperature dependent spring in (1) and taking the derivative to temperature ($T$), the following expression is found:

$$\frac{\partial V_{\mathrm{pi}}}{\partial T} = \sqrt{\frac{8}{27}}\,d\sqrt{\frac{k}{C_0}}\,\frac{\alpha+\beta}{2\sqrt{(1+(\alpha+\beta)T)}} = V_{\mathrm{pi}}\frac{\alpha+\beta}{2\sqrt{(1+(\alpha+\beta)T)}} \qquad (2)$$

From (2) it can be concluded that the pull-in thermal coefficient is not linear, and that it increases with temperature (note that $(\alpha + \beta) < 0$). For the device presented, and considering a constant temperature coefficient ($T = 0\,^{\circ}\mathrm{C}$ in (2)), a TC of $-149\,\mu\mathrm{V/K}$ results. Measurements were performed on a sample device (Fig. 4). The TC derived from these measurements is shown in Fig. 5, along with the value predicted by Eq. (2). The deviation between the two curves is significant, which suggests an effect other than the non-linearity in Eq. (2). Literature on the subject [14,15] report that the Young's Modulus temperature coefficient contains quadratic and higher terms in addition to the linear coefficient $\beta$ reported in [13]. Based on the data on the higher terms a second curve was computed and also presented in Fig. 5. The agreement is significantly improved (especially the trend) indicating that the cause of the non-linear pull-in TC is mainly due to the high non-linearity of the Young's Modulus TC.

## 4. Temperature compensation

The pull-in thermal coefficient can be easily calculated and measured as demonstrated in the last section. In instrumentation compensation and correction techniques are routinely applied to overcome, or at least to strongly reduce, any parasitic temperature dependency. Compensation at the lowest possible level in the data-acquisition chain (the sensor) is preferred to minimize the uncertainties introduced by subsequent components. Correction requires a separate

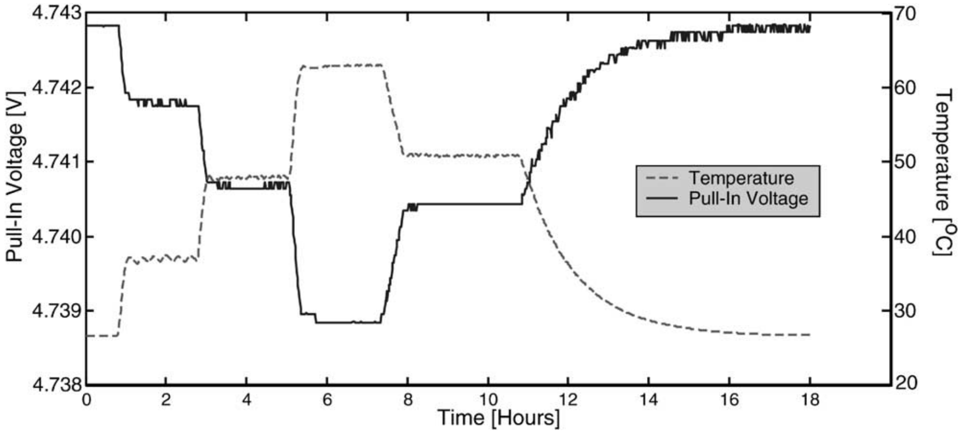

Fig. 4. Non-compensated device—pull-in vs. temperature.

measurement and manipulation at the data-processing level. The specifics of the pull-in structure enable a unique compensation approach to reduce the temperature dependence of the pull-in.

As $V_{\mathrm{pi}}$ is determined by the potential energy (electrostatic plus mechanical energies) in the system ($\partial^2 U_{\mathrm{p}}/\partial x^2 = 0$) and temperature decreases the mechanical energy ($\partial k/\partial T < 0$), a second set of electrodes can be used to add electrostatic energy with increasing temperature (on-device electro-mechanical compensation).

The second set of electrodes ($V_1$ in Fig. 2), enables the introduction of a positive TC (applying a voltage proportional to the square root of the measured temperature) compensating for the negative TC introduced by the mechanical properties. In order to check the change in the pull-in voltage with $V_1$, some measurements were performed (at constant temperature) and compared with computed values (Fig. 6). A slope $\partial V_{\mathrm{pi}}/\partial V_1^2 = 28.10^{-3}[\mathrm{V}^{-2}]$ was retrieved from the graph. To achieve zero TC: $(\partial V_{\mathrm{pi}}/\partial T)\Delta T + (\partial V_{\mathrm{pi}}/\partial V_1^2)\Delta V_1^2 = TC \cdot 1 + (\partial V_{\mathrm{pi}}/\partial V_1^2)\Delta V_1^2 = -10^{-4} + 28.10^{-3}\Delta V_1^2 = 0$, a value $\Delta V_1^2 = 3.55\,\mathrm{mV}^2/\mathrm{K}$ is required.

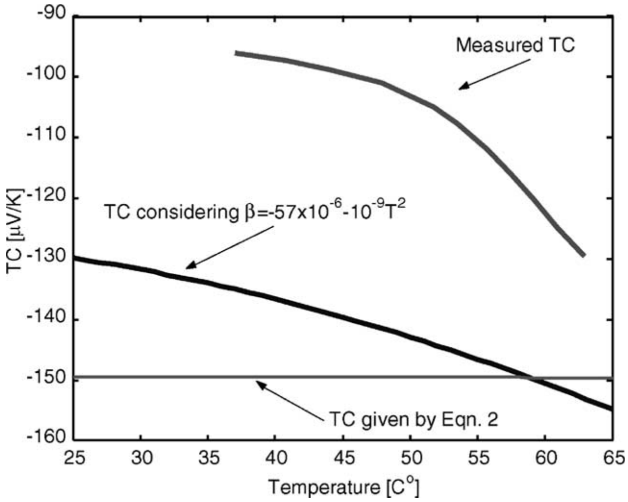

Fig. 5. Measured and simulated pull-in temperature coefficient (TC) vs. temperature.

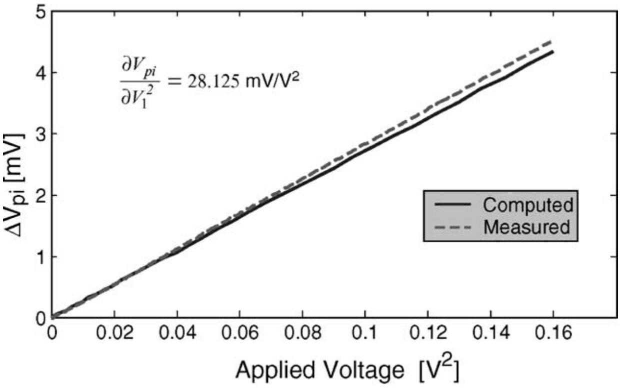

Fig. 6. Effect of compensation electrodes ($V_1$) on the pull-in voltage.

## 5. Experimental results

A feedback loop control for $V_1$, as presented in Fig. 7 was implemented to reduce the pull-in TC. A packaged microdevice in good thermal contact with a Pt-100 probe was placed in a climate chamber. The Pt-100 probe was used to measure the temperature of the structure and this information was used to generate the appropriate value for $V_1$ using the curve in Fig. 6. It should be noted that this method does

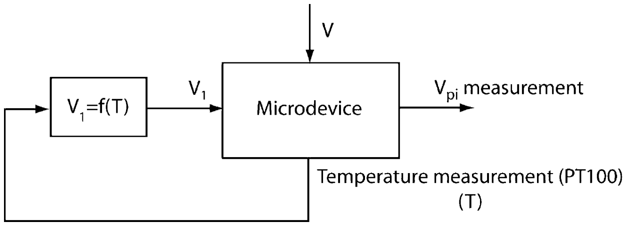

Fig. 7. Schematic of the implemented loop control for temperature compensation.

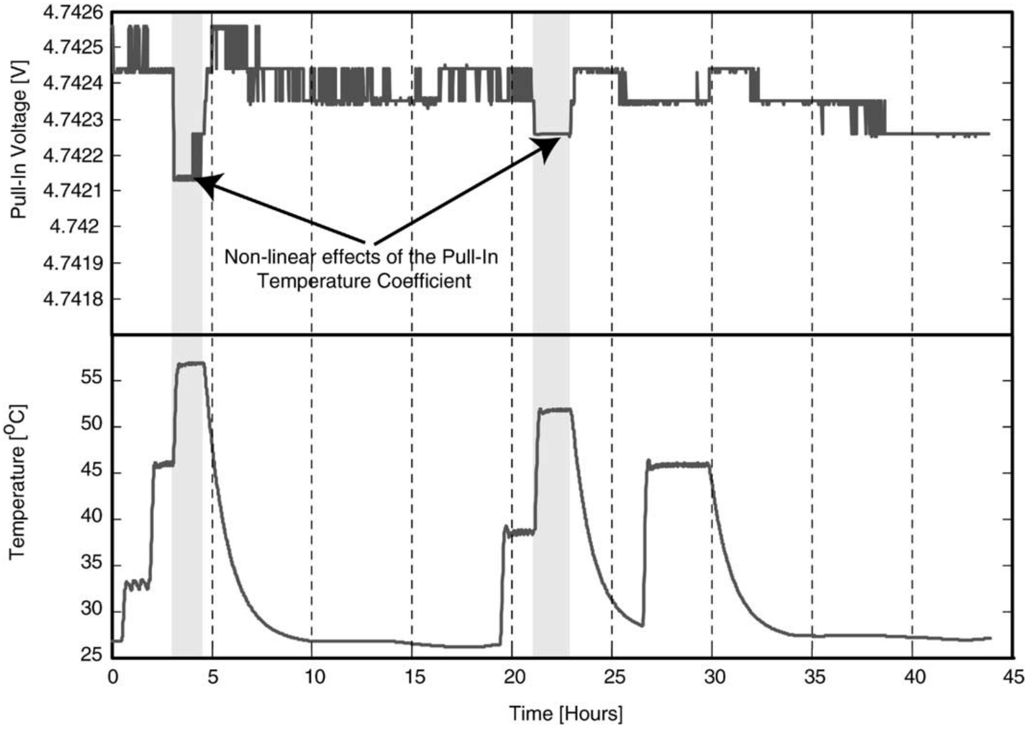

Fig. 8. Pull-in vs. temperature with compensation control.

not allow compensation for temperatures below the initial calibration temperature, because of the inherent quadratic relation between electrostatic force and voltage $V_1$.

Prior to these measurements, a burn-in for a period of about 80 h was performed to eliminate the charge effects [9], followed by varying the temperature in a range between 20 and 56 °C during a period of 45 h.

The results are presented in Fig. 8. The control was implemented on the assumption of a constant TC, thus does not take into account the non-linear terms of the Young's Modulus temperature coefficient. For temperatures beyond 50 °C, the non-linear effects become visible. A small charge-up effect is still visible (about 200 $\mu$V), indicating that for these devices a burn-in period of 80 h is not sufficient.

## 6. Conclusions

This compensation technique essentially includes both the electrical and mechanical domains. Conventional compensation would involve the measurement of the temperature and directly offsetting the pull-in voltage in the electrical domain. Such a technique would introduce a range of uncertainties originating from mechanical operation. As the compensation voltage is used here to drive a second electrostatic actuator, that has been fabricated in the same process and is matched to the primary actuator, such uncertainties are avoided.

Voltage references based on the pull-in voltage of a microstructure are ultimately limited by the mechanical noise of the structure, provided that the charge build-up effect and the temperature sensitivity are eliminated.

Although this work presents a major improvement, present devices do not yet compare very favorably with state-of-the-art in Zener diode based voltage standards. These are the most frequently used for transfer standards and typically demonstrate an instability less than $10^{-5}$ per year.

The mechanisms behind the charge built up and temperature sensitivity are well defined and well understood. The charge built-up, can be eliminated by coating the structure with a metal layer. As demonstrated, the temperature sensitivity is significantly reduced using the electro-mechanical compensation method presented. The uncompensated temperature dependence is reduced by 2–3 orders of magnitude. Although the nominal value of the reference element is of minor importance, some technological issues need to be addressed in order to improve device-to-device reproducibility.

In the introduction it was shown that pull-in voltage has been used to characterize the materials in surface micromachining process. This work shows that simple measurements as long-term pull-in, can be an excellent measure of the Young's Modulus temperature dependence (the dominant factor) and can be used to measure the charge density of the insulator layers formed during very high aspect ratio DRIE.

In this work, a new electro-mechanical approach for compensating the temperature dependence of pull-in was presented, and it was shown that it greatly reduces the TC. Present devices show a stable pull-in voltage within a

100 μV range (equipment resolution limit) over a temperature range of 40 K (273–313 K). Adequately temperature compensated devices have huge potential for practical operation as voltage reference element, due to the relatively high noise level of the Zener diode.

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## References

[1] S.T. Cho, K. Najafi, K.D. Wise, Internal stress compensation and scaling in ultra-sensitive silicon pressure sensors, IEEE Tr. ED 39 (1992) 836–842.

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

[3] H.A.C. Tilmans, R. Legtenberg, Electrostatically driven vacuum-encapsulated polysilicon resonators, part 2, theory and performance, Sens. Actuators A 45 (1994) 67–84.

[4] R. Nadal-Guardia, A. Dehé, R. Aigner, L.M. Castañer, Current drive models to extend the range of travel of electrostatic microactuators beyond the voltage pull-in point, J. Microelectromech. Syst. 11 (2002) 255–263.

[5] A.S. Oja, J. Kyynäräinen, H. Seppä, T. Lampola, A micromechanical dc-voltage reference, Conference Digest CPEM2000, Sydney, Australia, 14–19 May 2000, pp. 701–702.

[6] E. Cretu, L.A. Rocha, R.F. Wolffenbuttel, Using the pull-in voltage as voltage reference, Proceedings of Transducers'01, vol. 1, Munich, Germany, 10–14 June 2001, pp. 678–680.

[7] K.E. Petersen, Silicon as a mechanical material, Proc. IEEE 70 (1982) 420–457.

[8] J. Kyynäräinen, A.S. Oja, H. Seppä, Stability of micromechanical devices for electrical metrology, IEEE Trans. Instrum. Meas. 50 (2001) 1499–1503.

[9] L.A. Rocha, E. Cretu, R.F. Wollfenbuttel, Stability of a micromechanical pull-in voltage reference, IEEE Trans. Instrum. Meas. 52 (2003) 457–460.

[10] L.A. Rocha, E. Cretu, R.F. Wolffenbuttel, The pull-in of symmetrically and asymmetrically driven microstructures and the use in dc voltage references, Proceedings of IMTC'02, vol. 1, Anchorage, USA, 21–23 May 2002, pp. 759–764.

[11] http://www.europractice.bosch.com/en/start/index.htm.

[12] M. Offenberg, F. Lärmer, B. Elsner, H.Münzel, W.Riethmüller, Novel process for an integrated accelerometer, Proceedings of Transducers'95, vol. 1, Stockholm, Sweden, 25–29 June, pp. 589–593.

[13] Bosch, Micromachining Foundry Design Rules, version 2.01, 2000.

[14] W.N. Sharpe, M.A. Eby, G. Coles, Effect of temperature on mechanical properties of polysilicon, Proceedings of Transducers'01, vol. 1, Munich, Germany, 10–14 June 2001, pp. 1366–1369.

[15] H. Tada, A.E. Kumpel, R.E. Lathrop, J.B. Slanina, P. Nieva, P. Zavracky, I.N. Misoulis, P. Wong, Thermal expansion coefficient of polycrystalline silicon and silicon dioxide thin films at high temperatures, J. Appl. Phys. 87 (2000) 4189–4193.

## Biographies

*Luis Alexandre Rocha* was born in Guimarães, Portugal, in 1977. In 1995, he began to study electronic engineering at the University of Minho, Portugal, where he graduated in 2000. Since February 2001, he has been pursuing the PhD degree at the Department for Microelectronics, Faculty of Electrical Engineering Mathematics and Computer Science of the Delft University of Technology, Delft, The Netherlands. The topic of his research includes the study and design of MEMS for application in microinstruments.

*Edmond Cretu* was born in Romania in 1965. He received the MSc degree in electrical engineering from the "Politehnica" University of Bucharest in 1989, and the PhD from Delft University of Technology, in 2003. He was researcher in Romanian Academy and Associate Assistant at the Faculty of Electrical Engineering of "Politehnica" University of Bucharest. Since March 2000, he works for Melexis Belgium, as Senior Designer and Project Manager in the field of inertial systems, with emphasis on MEMS-based gyroscope systems.

*Reinoud F. Wolffenbuttel* received a MSc degree in 1984 and a PhD degree in 1988, both from the Delft University of Technology. Between 1986 and 1993 he has been an Assistant Professor and since 1993 he has been an Associate Professor at the Department of Microelectronics, Faculty of Information Technology and Systems of the Delft University of Technology and is involved in instrumentation and measurement in general and on-chip functional integration of microelectronic circuits and silicon sensor, fabrication compatibility issues and micromachining in silicon and microsystems in particular. He was a visitor at the University of Michigan, Ann Arbor, USA in 1992, 1999 and 2001, Tohoku University, Sendai, Japan in 1995 and EPFL Lausanne, Switzerland in 1997. He is the recipient of a 1997 NWO pioneer award. He served as general chairman of the Dutch national sensor conference in 1996, Eurosensors in 1999 and the MicroMechanics Europe Workshop in 2003.