Stability of a Micromechanical Pull-In Voltage Reference

Luis A. Rocha, Edmond Cretu, and Reinoud F. Wolffenbuttel

***Abstract*—The reproducibility over temperature and time of the pull-in voltage of micromechanical structures has been analyzed and verified using fabricated devices in silicon. The pull-in structures are intended for use as an on-chip voltage reference. Microbeams of 100-μm length, 3-μm width, and 11-μm thickness are electrostatically actuated with a very reproducible pull-in voltage at 9.1 V. Devices demonstrated an initial drift of -12 mV over 10 days and stabilized within the 500-μV measurement uncertainty. The measured temperature coefficient of -1 mV/K is in good agreement with the analysis and is due to the combined effect of thermal expansion and the temperature dependence of the Young's modulus in silicon.**

***Index Terms*—DC voltage reference, microelectromechanical systems (MEMS), pull-in stability, reproducibility.**

I. Introduction

THE pull-in voltage of a micromechanical structure has been proposed as voltage reference [1], [2]. Such a device may find application as a transfer standard with superior performance as compared to the Zener diode in terms of stability and noise, as operation of the latter is based on avalanche breakdown. A key specification of these devices is the time and temperature stability and is addressed in this paper.

The basic pull-in device is a simple single-side clamped beam with an electrostatic actuation voltage applied, which results in a displacement proportional to the square root up to the pull-in voltage at about one third of the width of the initial gap between the electrodes. As the electrostatic force in a vertical field is inversely proportional to the square of the deflection and the restoring force of the beam is, in a first approximation, linear with deflection, an unstable system results in case of a deflection v beyond a critical value $v_{\rm crit}$. This pull-in voltage $V_{\rm pi}$ is thus defined as the voltage that is required to obtain this critical deflection [3]. For a stable equilibrium deflection, the second derivative of the potential energy of the system to deflection should be positive: $\partial^2 U_p/\partial V^2 > 0$, thus $V_{\rm pi}$ results from $\partial^2 U_p/\partial V^2 = 0$ and is uniquely determined by the beam material, the beam dimensions and the residual stress. The potential energy is composed of the elastic mechanical energy $U_{\rm elastic}$ and the electrostatic energy stored in the electric components $U_{\rm electric}$. The elastic energy has two components: the built-in strain energy component $U_{\rm built-in}$ and the bending energy resulting from external applied forces $U_{\rm bending}$.

Micromanufactured silicon beams usually exhibit residual stress, which is part of $U_{\rm built-in}$. This property not only causes buckling of a double-sided clamped beam, but also results in a time and temperature dependence. It, therefore, significantly determines the load-deflection characteristic, as this stress level cannot be released in an elongation. The pull-in voltage of such a double-sided clamped structure reduces with compressive stress, which makes it unsuitable as a voltage reference. Moreover, the reproducibility would be limited by long-term drift due to stress relaxation. In the application presented here, the pull-in voltage is exploited for the realization of a dc voltage reference. For long-term stability, the residual stress should not affect $V_{\rm pi}$. Therefore, a single-sided anchored beam with the other end free-standing should be used or the beam should be suspended using folded tethers at each end [4]. Both approaches ensure $U_{\rm built-in} = 0$.

Even with this type of implementation, a number of sources of uncertainty remain. These are a direct consequence of basic device operation. Three temperature-related parasitic effects can be identified. The first is the thermal expansion of the single-sided clamped beam. As the basic operation is the force balance between a surface effect (the electrostatic force) and a bulk effect (the mechanical force due to the compliance of the beam), the pull-in voltage necessarily depends on the dimensions of the beam. The compliance of the beam is predominantly inversely dependent on the length, which increases with temperature. The second temperature effect is due to the temperature dependence of the modulus of elasticity (Young's modulus, E), which is generally described by a negative temperature coefficient. The modulus of elasticity is included linearly in the expression for the compliance and thus in the pull-in voltage. These combined effects, therefore, result in a negative temperature coefficient, TC, for $V_{\rm pi}$. The third temperature dependence is due to the fact that the beam is moving in a gaseous medium. The viscosity of the surrounding gas mainly provides damping, which does not affect the pull-in voltage. However, at very fast displacements, the incompressibility of the gas demonstrates as an additional compliance. This additional spring is in parallel to that of the beam. As mentioned, pull-in is basically the sudden collapse of the beam at an increasing voltage. This implies a very abrupt movement with high-frequency components. Under typical operating conditions, this effect can usually be ignored, as will be presented later.

In addition to temperature effects, the basic device operation also gives rise to time dependencies. In almost any electrostatically operated device, the electrostatic field is prone to parasitic

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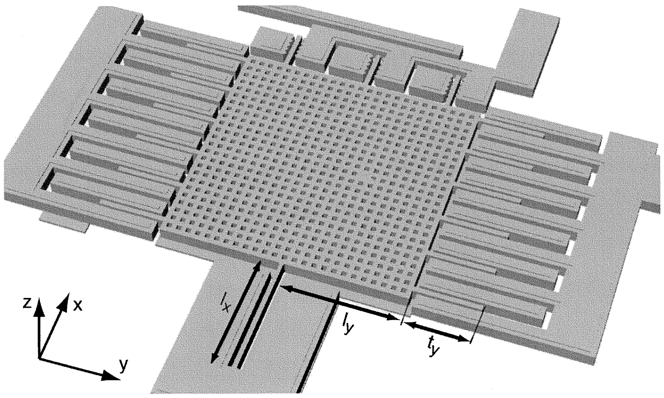

Fig. 1. Single-side clamped structure drawing.

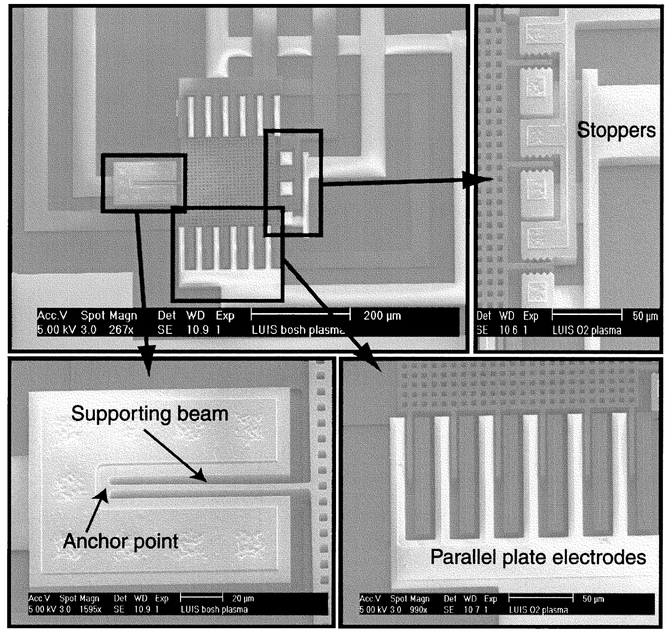

Fig. 2. Photograph of the micromechanical device.

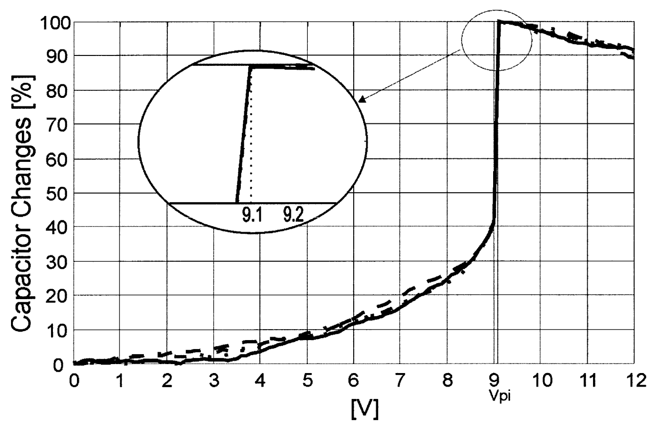

Fig. 3. Experimental pull-in result for four beams showing good sample-to-sample reproducibility.

charge build-up, and surface charges have an important role on the electrical stability. These are primarily due to: 1) charge introduced during device manufacturing and 2) charges trapped in dielectrics during device operation (in silicon these are often the native oxides layers on top of the electrodes) that yield an electrostatic force while no voltage is applied [5]. In particular, the trapped charges tend to result in a polarity-dependent drift [6] in long-term operated micromechanical structures.

II. Device Operation

A single-sided clamped beam has been designed and used in which the electrostatic forces are counteracted by both mechanical forces and momentums in the structure (Fig. 1). The predicted pull-in voltage from the analytical model [7] is at $V_{\mathrm{pi}} = 9.6$ V and is in reasonable agreement with experimental results.

A modification on surface micromachining, a so-called epi-poly process [8], [9], was used for the fabrication of 11-μm-thick single-sided clamped 100-μm-long free-standing test structures with electrodes (Fig. 2). The device is basically a free-standing lateral beam anchored at one end (the base) only. The beam can be deflected by electrostatic actuation in the plane of the wafer using a voltage applied across parallel plate capacitors composed of two sets of electrodes located alongside the free-standing tip, with counter electrodes anchored to the substrate. The deflection can be measured using the differential sense capacitor located directly on top of the substrate and aligned with the square-shaped electrode at the tip of the beam. These buried polysilicon electrodes are electrically isolated from the substrate and placed symmetrically on either side of a guard electrode placed directly underneath the axial direction of the nondeflected beam. Finally, there are electrically isolated stoppers to limit the lateral motion. After completion of the surface micromachining process, the structures were diced and enclosed under a protective cap. The capped dices are enclosed in Neon at a pressure of 600 mbar.

III. Experimental Results

Small step increments are applied to the structure, and through capacitance readout the pull-in voltage is measured. Fig. 3 shows the response of a typical device measured directly. Different devices have been measured over a period of time at constant temperature (22 ± 1)°C. The pull-in voltage of one beam over 26 days is presented in Fig. 4.

Other devices have been subjected to thermal cycling. The measurements were performed after stabilization during a two-week burn-in period. Fig. 5 shows one of those measurements which indicates a temperature coefficient of about -1 mV/K.

IV. Discussion

Analyzing Figs. 4 and 5, two different characteristics are observed. The first one is the drift during the first 10 days (Fig. 4) and stabilization afterwards and the second characteristic is the dependence of the pull-in voltage on temperature (Fig. 5).

As already mentioned, the initial drift is expected to be due to charging of the dielectric layer between the electrodes. The temperature dependence is caused by beam elongation and the temperature dependence of the modulus of elasticity. Both of

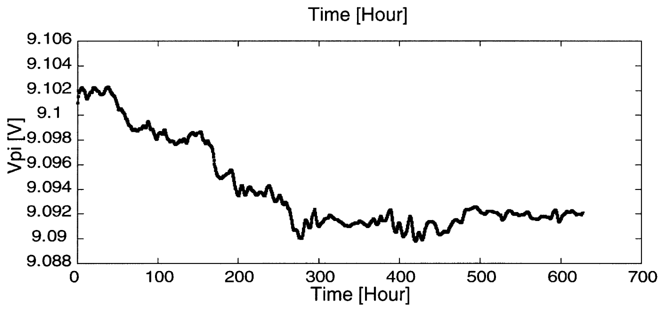

Fig. 4. Stability test at a constant temperature.

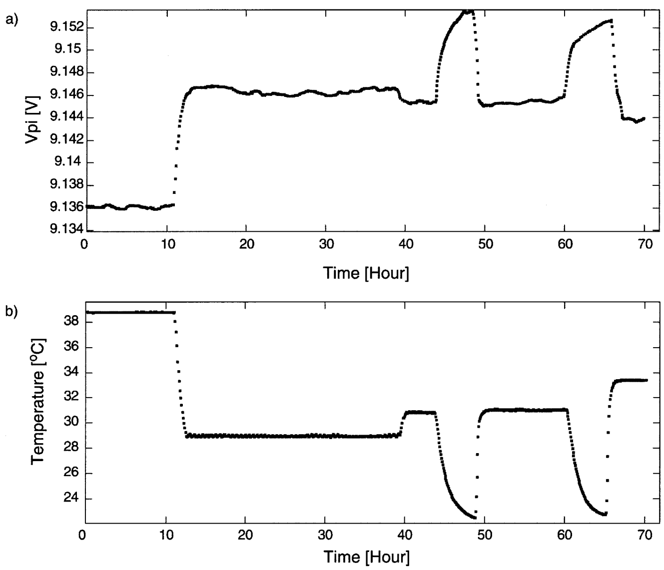

Fig. 5. Stability test. (a) Pull-in voltage. (b) Temperature.

these characteristics will be analyzed quantitatively in this section.

A. Surface Charging

During the fabrication of the devices, a Teflon-like film is deposited on the sidewalls [10]. This polymer, used as a passivation layer and deposited during plasma etching, is not removed at the end and is a very likely cause of the −12–mV drift observed over the first 10 days. The electrostatic force between electrodes considering the presence of trapped charges on the electrode surface has been derived [5] and can be written as

$$F = \frac{1}{2}\frac{dC}{dx}(V - V_{\text{offset}})^2 \text{ with}$$
$$V_{\text{offset}} = -\frac{d_{\text{polymer}}}{\varepsilon_{\text{polymer}}}\sigma_{\text{polymer}} \tag{1}$$

where V_{offset} is an offset voltage leading to a shift of the parabolic force versus voltage curve due to trapped charges, d_{polymer} is the thickness of the polymer layer, $\varepsilon_{\text{polymer}}$ is the polymer permittivity, and σ_{polymer} is the charge density. Values found in the literature for Teflon-like layers report a $\varepsilon_{\text{polymer}} = 1.9\varepsilon_0$ and $\sigma_{\text{polymer}} = 1.25 \times 10^{10}$ e/cm^2 [11]. Typical values for the thickness of the polymer layer are on the order of a few nanometers. Considering a very realistic value, such as $d_{\text{polymer}} =$

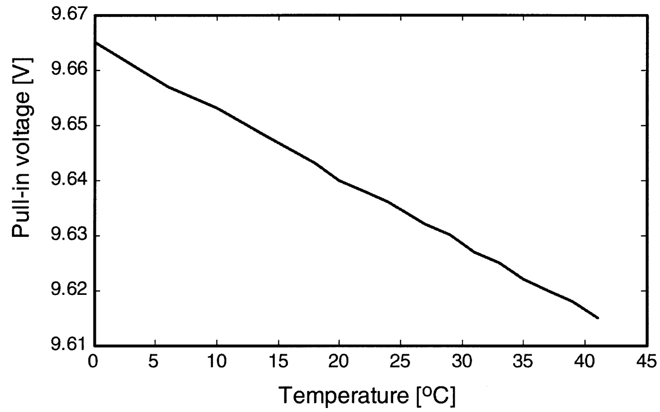

Fig. 6. Pull-in voltage versus temperature.

8 nm, yields $V_{\text{offset}} = -9.5$ mV, clearly in agreement with the observed drift.

This can be experimentally validated with an extra etching step (oxygen plasma etching) to remove the polymer in order to minimize the initial drift.

B. Effect of Thermal Expansion on the Pull-In Voltage

The source of the temperature dependence of the pull-in voltage appears to be the thermal expansion of the polysilicon and the Young's modulus changes with temperature. Both of these properties of the material change the mechanical spring constant of the system, leading to changes in the voltage required to reach the critical deflection (pull-in voltage).

To verify the influence of temperature on the pull-in voltage, the model derived in [7] has been used. Basically, the total energy of the system is computed, and by sweeping the voltage from zero toward increasing positive values the stability is checked. When the system becomes unstable, the pull-in voltage is found.

The equivalent mechanical scheme of the structure is that of a clamped rectangular beam subjected at the free end to a horizontal force F_{el} and to a bending momentum M_{el} resulting from the electrostatic forces. In this case, the bending w_1 and the bending angle φ_1 will be given by [12]

$$w_1 = \frac{l_x^2}{6EI}(2l_xF_{\text{el}} + 3M_{\text{el}}) \tag{2a}$$
$$\varphi_1 = \frac{l_x}{2EI}(l_xF_{\text{el}} + 2M_{\text{el}}) \tag{2b}$$

where E is the Young's modulus, I is the moment of inertia, and l_x is the beam length. From the bending equations, we can derive the mechanical spring constant of the structure k as a 2×2 matrix defined as

$$k = \frac{EI}{l_x}\begin{pmatrix} \frac{12}{l_x^2} & -\frac{6}{l_x} \\ -\frac{6}{l_x} & 4 \end{pmatrix}. \tag{3}$$

As shown in (3), k depends only on device dimensions and material properties, and so is very prone to temperature changes. We know from data of the surface micromachining process used to fabricate the devices [8] that the thermal expansion coefficient of polysilicon is $\alpha = 3 \times 10^{-6}$/K and that the Young's modulus in GPa decreases with temperature in °C as $E = 163 -$

$0.042 \times T$ [13]. By introduction of this data in the model, the pull-in voltage dependence on temperature can be determined. The pull-in voltage has been computed for a temperature range of 40 °C and the results are presented in Fig. 6. From the slope of the curve, we can derive a -1.2–$\mathrm{mV/K}$ temperature coefficient.

V. Conclusion

Preliminary results of long-term measurements on the pull-in voltage of a micromechanical structure have been presented. The stability is shown to be limited by a temperature dependence and an initial "burn-in" effect. The cause for the temperature dependence is attributed to the thermal expansion of the material and TC of the Young's modulus. Analytical results fit well with experimental results and methods to eliminate this great temperature dependence must be studied. One possibility is by exploiting the spring effect of the surrounding gaseous medium.

The time dependence of the pull-in voltage is another observed effect and is shown to be due to charging of a polymer layer. By removing this layer, the effect could be minimized. Another way to overcome the charge effect could be the coating of the electrodes with a metal, but this step is technologically more difficult to implement.

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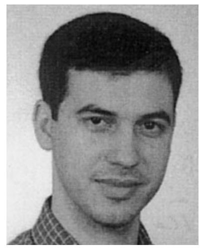

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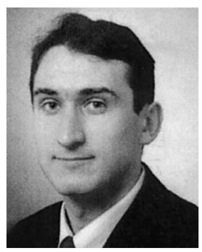

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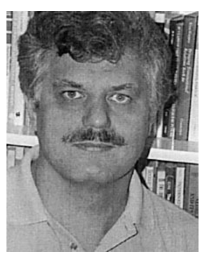

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