Full characterisation of pull-in in single-sided clamped beams

L.A. Rocha*, E. Cretu1, R.F. Wolffenbuttel

Department for Microelectronics, Faculty of ITS, Delft University of Technology, Mekelweg 4, Delft 2628 CD, The Netherlands

Received 22 October 2002; accepted 5 September 2003

Abstract

The most striking characteristic of the voltage-to-deflection curve of an electrostatically actuated beam is pull-in. The actual value of the pull-in voltage depends on: drive mode, temperature dependence and dielectric charging related drift. These aspects have been analysed using structures designed for a 9 V nominal pull-in voltage and fabricated in a commercially available epipoly process. Single-sided clamped beams have been used to avoid any influence of residual stress in the beam on pull-in. Typical results are: less than 5% variation of the pull-in voltage over a wafer, 0.17–1.9 V hysteresis depending on drive mode, a \(-1 mV/K\) TC and \(-12 mV\) drift during the first 2 weeks of operation.

© 2003 Elsevier B.V. All rights reserved.

Keywords: DC voltage reference; MEMS stability; Reproducibility; Pull-in

1. Introduction

Microelectromechanical systems benefit from the relatively intensive coupling between different energy domains (electrical, mechanical, thermal) at the microscale level [1,2]. One important phenomenon observed in the coupling between the electric and mechanical domains is pull-in. This inherent instability in electromechanical devices has been subject of several studies. As it depends mainly on dimensions, residual stress level and design, it has been used to characterise structural materials in surface micromachining processes [3,4]. Unlike the case of the comb drive, the design of electrostatic actuators relying on a vertical field has to consider the pull-in phenomenon [5]. Pull-in causes the deflection due to electrostatic force to be limited to one-third of the gap between the electrodes, in case of a motion perpendicular to the capacitor plate orientation. 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 [6]. Recently, the pull-in has been proposed for use as a voltage reference [7,8]. As silicon has good and stable mechanical properties [9], a voltage reference based on the pull-in voltage should be feasible.

In the application presented here the pull-in voltage is exploited for the realisation of a DC voltage reference. Such a device may find application as a transfer standard with superior performance as compared to the Zener in terms of stability and noise, as operation of the later is based on avalanche breakdown.

The simplest micromechanical system suitable for studying the stability of the pull-in voltage is composed of two electrodes, one of them movable and connected to a suspension beam with a certain stiffness \(k\) (Fig. 1). 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, \(v_{\text{crit}}\). The pull-in voltage, \(V_{\text{pi}}\), is defined as the voltage that is required to obtain this critical deflection [5]. 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 \(V_{\text{pi}}\) results from \((\partial^2 U_p/\partial v^2) = 0\) and is determined by the beam material, the beam dimensions, residual stress, and the electrodes dimensions (electrostatic energy).

In a microelectromechanical system with interaction between the electrical and mechanical domain, the potential energy is composed of the elastic mechanical energy, \(U_{\text{elastic}}\), and the electrostatic energy stored in the electric component, \(U_{\text{electric}}\). The elastic energy has two components: the
build-in strain energy component, $U_{\text{build-in}}$, and the bending energy resulting from external applied forces, $U_{\text{bending}}$.

Micromanufactured silicon beams usually exhibit residual stress, due to fabrication, which is part of $U_{\text{build-in}}$. This property not only causes buckling of the beam, but also results in a time and temperature dependence. It, therefore, significantly determines the load-deflection characteristic in a double-sided clamped structure, as this stress level cannot be released in an elongation. As the reproducibility of such a structure would be limited by the long-term drift due to stress relaxation, the pull-in voltage of a double-sided clamped structure is not suitable as a voltage reference. For long-term stability the residual stress should not affect $V_{\text{pi}}$. 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 [10]. Both approaches ensure $U_{\text{build-in}} = 0$.

Even if these precautions have been implemented, a number of sources of uncertainty remain. These are a direct consequence of basic device operation. The pull-in voltage shows a temperature coefficient. Obviously, thermal expansion of the single-sided clamped beam has to be considered, as the basic operation is the force balance between a surface effect (the electrostatic force) and a bulk effect (the compliance of the beam). For long-term stability the residual stress should not affect $V_{\text{pi}}$. 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 [10]. Both approaches ensure $U_{\text{build-in}} = 0$.

In addition to temperature effects, the basic device operation also gives rise to time dependencies. Not unlike any other electrostatically operated device, the electrostatic field is prone to parasitic charge build-up. 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) yield an electrostatic force while no voltage is applied [11]. Especially, the trapped charges are the cause of polarity dependent drift [12] in long-term operated micromechanical structures.

In this paper, a full characterisation of pull-in is pursued, which includes the effect of the sources of uncertainty mentioned. A two degrees of freedom analytical model [13] is used to compute the pull-in for different actuation modes and results are compared with experimental data obtained from different test structures. Long-term measurements have been performed to verify the drift mechanism due to oxide charging. Thermal cycling has been carried out to verify the predicted susceptibility to changes in ambient temperature.

2. Device operation

Two different single-sided clamped beam structures have been used for studying pull-in (Fig. 2). These have different dimensions, but both reveal the same two degrees of freedom behaviour to be characterised.

The structures allow two types of actuation: symmetric and asymmetric. In case of asymmetric actuation, the voltage is applied between two sets of electrodes only; the upper right and bottom left electrodes, yielding an unbalanced electrostatic momentum counteracted by the restoring elastic force. In case of a symmetric drive, the voltage is applied across all four sets of electrodes (Fig. 2).

Associated to the pull-in, and to the voltage actuation used in this work is the pull-in bi-stable regime, also called...
hysteresis [14]. When pull-in occurs, there is an unbalance between electrostatic force and elastic force, which is compensated by a reaction force when the movable part hits its final position. For reliability reasons and for avoiding electrical short-circuiting, the test structures are designed with stoppers to stop the movable part on a well-known position. It should be emphasised that the hysteresis in such a MEMS device is not due to a parasitic or practical device limitation, such as sticking. Rather, it is fundamental to basic device operation. The stopper position is not the cause of hysteresis, but its position affects the hysteresis magnitude.

3. Test structures fabrication

The epipoly process was used for the fabrication of the tested structures [15,16]. 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.

This process is used for fabrication of thick polysilicon structures, which are more likely to have stress and stress gradients in vertical and lateral direction, as compared to devices fabricated in crystalline silicon. A part of this research is to investigate whether the resulting stability is impaired to an extent that bulk micromachined structures should be used.

3.1. Structure 1: inverted pendulum with vertical sense capacitors

This device is basically a free-standing lateral beam (100 μm long, 3 μm wide and depth of 10.6 μm) anchored at one end (the base) only (Fig. 3). 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 is measured using the differential sense capacitor located directly on top of the substrate and...
aligned with the square-shape 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 directly underneath the axial direction of the beam. Finally, there are electrically isolated stoppers to limit the lateral motion. The electrodes beneath the movable structure are used for capacitive detection of the pull-in voltage.

3.2. Structure 2: inverted pendulum with interdigitated finger sense capacitor

The second studied structure is very similar to the first (Fig. 4). The difference is that on this one, the differential sense capacitors are not located on top of the substrate, but alongside the free-standing tip. This also applies to the actuator capacitors. The free-standing beam is 200 \( \mu \)m long, 3 \( \mu \)m wide and 10.6 \( \mu \)m thick.

4. Experimental results

Structures of type 2 are subjected to pull-in tests. In the next sections, the results are presented and compared with model predictions [13]. Moreover, preliminary long-term measurement results on structure 1 are presented and discussed.

Pull-in is measured by capacitance readout in all structures. A voltage is applied to the actuator capacitors and pull-in is detected by the sudden change in capacitance.

4.1. Inverted pendulum: structure 2

The schematic of the device is shown in Fig. 2. The predicted pull-in voltage from the analytical model for the asymmetric case is \( V_{pi} = 9.24 \) V. The pull-in voltage for the symmetric mode of operation was also computed, as well as the release voltages for both operation modes (using the 2D hysteresis model presented before [13]). Fig. 5 shows the predicted behaviour of the structure for both actuation modes. At this stage, it is important to note that the asymmetric mode can be operated in two ways (refer to Fig. 2): voltages can be applied on the bottom right and top left electrodes—asymmetric right—or the top right and bottom left electrodes can be actuated—asymmetric left. These two different approaches for asymmetric drive, along with the symmetric drive (all electrodes are driven) have been applied to the fabricated structures. Fig. 6 presents the measured pull-in voltages for the three types of actuation. Unexpectedly, different values for the pull-in voltage are measured for the different types of asymmetric actuation. This indicates that the structure (the beam) is not at a central position, as expected, but has an initial bending. Residual stress and (vertical and lateral) gradients therein are usually present in a structural layer fabricated in a surface micro-machining process. The fact that this structure is clamped at one side only ensures that the residual stress does not affect the pull-in of the beam. However, a stress gradient would displace the structure from the initial zero position.

4.1.1. The effect of stress gradients on the pull-in voltage

Among the mechanical properties specified for the epipoly structural layer is a vertical stress gradient of 1.3 \( \pm \) 2 MPa/\( \mu \)m [17] (i.e. in the direction normal to the plane of the wafer). This stress gradient can not be the cause of the different pull-in voltages measured, because such a gradient would cause a bending of the beam away from the substrate plane, causing no change on the initial zero position. The in-plane (lateral) stress gradient (i.e. parallel to the plane of the wafer) are not explicitly specified, but is estimated at 0.2 MPa/\( \mu \)m. This value is used to check the influence on the pull-in voltage.

If a new mechanical energy component, \( U_{\text{grad-stress}} \), calculated using the in plane 0.2 MPa/\( \mu \)m stress gradient, is introduced in the model, we can trace the pull-in for the two types of asymmetric drive (either considering a positive or negative \( U_{\text{grad-stress}} \), and also check the effect of this unbalance on the symmetric pull-in.

Table 1 presents the results obtained. The comparison of the predicted values with the experimental ones indicates good agreement. The small deviations (less than 5%) are due to process tolerances and uncertainties on the value of the Young’s modulus. Introduction of bending caused by a stress gradient in the model leads to a much better agreement with experimental results. This is especially true for the symmetric case, where the incorrect assumption of a sta-
ble central initial position where the electrostatic forces become equal, has the most impact. However, because of bending caused by the stress gradient, the electrostatic forces are not in equilibrium, resulting in a small initial deflection and consequently in a pull-in at a lower voltage than previously computed.

4.2. Long-term measurements: structure 1

After the characterisation of the different actuation types, some other devices have been used for long-term stability measurements. We were interested in checking whether the pull-in voltage is constant in time, and if long-term measurements of the pull-in can be used to give more details on the material properties.

Fig. 5. Results of the 2DOF model for a device (a) asymmetrically and (b) symmetrically driven.

The pull-in voltage of the second structure has been measured over 26 days at constant temperature (22 ± 1 °C) and the result is presented in Fig. 7. Other devices have been measured at changing temperatures. The measurements were performed after stabilisation during a 2-week burn-in period. Fig. 8 shows one of those measurements. A temperature coefficient of about −1 mV/K is observed.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Asymmetric right</th>
<th>Asymmetric left</th>
<th>Symmetric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{pi}$ (V)</td>
<td>$V_{r}$ (V)</td>
<td>$V_{pi}$ (V)</td>
</tr>
<tr>
<td>Analytical model results</td>
<td>9.06</td>
<td>9.01</td>
<td>9.41</td>
</tr>
<tr>
<td>Experimental results</td>
<td>9.34</td>
<td>9.27</td>
<td>9.61</td>
</tr>
</tbody>
</table>
Fig. 6. Experimental results for a device (a) asymmetrically right, (b) asymmetrically left and (c) symmetrically driven.

From Figs. 7 and 8, two interesting performance characteristics are observed. The first one is the drift during the first 10 days (Fig. 7) and stabilisation afterwards and the second characteristic is the dependence of the pull-in voltage on temperature (Fig. 8).

The initial drift is expected to be due to charging of a dielectric layer between the electrodes. The temperature dependence is caused by beam elongation and the temperature dependence of the modulus of elasticity. Both this characteristics will be analysed quantitatively in this section.
4.2.1. Surface charging

During the fabrication of the devices, a teflon-like film is deposited on the sidewalls [18]. 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 $-12\text{ mV}$ 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 on [11] and can be written as:

$$F = \frac{1}{2} \frac{dC}{dx} (V - V_{\text{offset}})^2,$$

where

$$V_{\text{offset}} = -\frac{d_{\text{polymer}}}{\varepsilon_{\text{polymer}}} \sigma_{\text{polymer}}$$

(1)

where $V_{\text{offset}}$ is an offset voltage leading to a shift of the parabolic force versus voltage curve due to trapped charges, $d_{\text{polymer}}$ is the thickness of the polymer layer, $\varepsilon_{\text{polymer}}$ is the polymer permittivity and $\sigma_{\text{polymer}}$ is the charge.
density. Values found in literature for teflon-like layers report a \( \varepsilon_{\text{polymer}} = 1.9 \times 10^{-9} \) and \( \sigma_{\text{polymer}} = 1.25 \times 10^{11} \text{ e/cm}^2 \) [19]. Typical values for the thickness of the polymer layer are on the few nm. Considering a very realistic value, such as \( d_{\text{polymer}} = 8 \text{ nm} \) yields a \( V_{\text{def}} = -9.5 \text{ mV} \), clearly in agreement with the observed drift.

4.2.2. Effect of temperature 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 dependence on temperature. Both properties change the mechanical spring of the system, leading to changes in the voltage required to get the critical deflection (pull-in voltage).

To verify the influence of temperature on the pull-in voltage, a 2-DOF analytical pull-in model [13] has been used. Both electrical and mechanical energy depends on the dimensions of the structure (the beam for the mechanical energy and the capacitor for the electrical energy). For the epipoly process used to fabricate the devices [17], a polysilicon with thermal expansion coefficient \( \alpha = 3 \times 10^{-6} \text{ K}^{-1} \) is specified and the Young’s modulus thermal coefficient is \( \beta = -67 \times 10^{-6} \text{ K}^{-1} \). Introduction of this data in the model leads to a value of the temperature dependence of the pull-in voltage. The pull-in voltage has been computed between 0 and 40°C and yields a \( -0.5 \text{ mV/K} \) temperature coefficient, which is in reasonable agreement with measurements.

5. Conclusions

In electrostatic actuators and servo-operated capacitive accelerometers the displacement range should be maximum. Although the symmetric drive offers a higher pull-in voltage, Fig. 6 clearly indicates that the usable displacement is very limited due to the more sudden pull-in. For this reason, the asymmetric drive with the more gradual displacement-to-voltage characteristic is to be preferred in this application.

For proper operation of a pull-in structure as a voltage reference, the pull-in should be as abrupt as possible and the effect should be reproducible. The symmetric drive has a better defined threshold with an abrupt pull-in. However, for use as a dc voltage reference, where stability and device-to-device reproducibility is crucial, the asymmetric drive offers superior operational performance as compared to the symmetric one. Therefore, also in this application area, the asymmetric drive should be selected.

Due to the dependence on process tolerances, the symmetric drive can be used as good process monitor. Its displacement versus voltage characteristic may also be helpful in obtaining a better insight in the dependence on fundamental design parameters and influence of tolerances and parasitic effects on the pull-in voltage.

The asymmetric drive can be used as a versatile test structure for measuring in-plane stress gradients in the structural layer in a surface micromachining process, by alternatively applying the voltage to the upper left–lower right and lower left–upper right electrodes.

The temperature coefficient of the pull-in voltage is significant, but is accurately predictable and thus can be corrected or compensated for. The major source of drift is relaxation of change in a dielectric layer, which can be significantly reduced by proper surface treatment.

Acknowledgements

This work is supported by the Netherlands Technology Foundation (STW) under grant DE15.5733.

References

Biographies

L.A. 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. From 1999 to 2001, he worked in a company developing systems on the area of automation and control. Since February 2001, he has been pursuing the PhD degree at the Department for Microelectronics, Faculty for Information Technology and Systems 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.

E. Cretu was born in Romania in 1965. He received the MSc degree in Electronic engineering from the polytechnic university of Bucharest in 1989. He is currently pursuing the PhD degree at the department for Microelectronics of the Delft University of Technology, Delft, The Netherlands. He was a researcher at the Romanian Academy of Sciences and as an Associate Assistant at the Faculty of Electrical Engineering of the Polytechnic University of Bucharest. Since March 2006, he has been with Melexis Belgium, where he is involved in the development of gyroscopes.

R.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 1997 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.