Stability of Voltage References based on the Pull-in of a Micromechanical Structure

L.A. Rocha and R.F. Wolffenbuttel
Delft University of Technology, Faculty ITS, Department for Microelectronics,
Mekelweg 4, 2628 CD Delft, The Netherlands

SUMMARY

Micromechanical structures have been designed, fabricated in silicon and tested for use as on-chip voltage reference. Applications are in electrical metrology and in integrated silicon microsystems. Microbeams of 100 µm length, 3 µm width and 11µm 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 with a 500 µV uncertainty. The temperature coefficient is -1 mV/K.

Keywords: MicroElectroMechanical Systems (MEMS), DC voltage reference, pull-in.

INTRODUCTION

A critical component in many professional instruments is the internal DC reference. The pull-in voltage of beams of different designs has been investigated with the purpose of using the micromechanical structure as an on-chip voltage reference [1,2]. Such a device may find application in integrated circuits, as alternative to the bandgap reference, and in metrology, where Zener references are widely used as so-called “transfer standard”.

The basic pull-in device is a simple single-side clamped beam with an electrostatic actuation voltage applied. 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. The pull-in voltage, \( V_{pi} \), is thus defined as the voltage that is required to obtain this critical deflection.

So far the pull-in effect has been mainly investigated for two reasons. The first is to determine the dynamic range limitations of an electrostatic actuator due to pull-in [3], as pull-in causes the deflection due to electrostatic force to be limited to 1/3 of the gap between the electrodes. The second application area is in the characterization of the structural material in a surface micromachining process [4].

The stability of a pull-in voltage reference is discussed in this paper. A single-sided clamped beam fabricated using crystalline material was used, with different actuation modes (symmetrically and asymmetrically). The single-end clamping ensures that the pull-in is insensitive to technology-induced strains.

OPERATION ANALYSIS

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). Two types of actuations have been studied:

a) Asymmetric actuation – voltages are applied between the beam and bottom right and top left electrodes.

b) Symmetric actuation – all four electrodes used.

Fig. 1: Schematic of the single-side clamped structure.

A simple qualitative analysis shows that the symmetric drive yields a larger pull-in voltage as compared to driving the same device asymmetrically. This is due to fact that in the asymmetrically operated device, the electrostatic energy is counteracted by the elastic beam energy until the beam collapses at the pull-in threshold. In the symmetric case, however, the electrostatic fields are in a first order approximation balanced. Beyond a certain voltage level the beam nevertheless collapses, due to asymmetries in the structure. The balancing in the electrostatic domain causes the pull-in to take place at a higher voltage level. The higher pull-in voltage at given device dimensions could be an advantage. However, the dependence on device asymmetries and imperfections, and thus on device fabrication, is likely to favor the asymmetric drive. The predicted pull-in voltage from the analytic model is at \( V_{pi} = 9.6V \) for the asymmetric case and at \( V_{pi} = 12.5V \) for the symmetric one.
**HYSTERESIS**

An important aspect of movable microelectromechanical systems like the one presented here is that it requires a stop position, which in turn causes mechanical hysteresis [5]. In our case, this phenomenon is important, as it seriously complicates the design of a feedback system required to control the structure. It should be emphasized 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 the basic device operation. The stopper should be positioned somewhere between the deflection at pull-in, $x_n=1/3$ and $x_n=1$ to prevent the beam from hitting the counter electrode and thus compromising reliability and short-circuiting the capacitor.

The hysteresis phenomenon can be demonstrated using the one degree of freedom case of a parallel plate structure. Computing both the electrostatic and mechanical force for such a case we can see the evolution of the equilibrium position with increasing voltage (Fig. 2). Pull-in occurs when the mechanical force can no longer be made equal to the electrostatic force ($V=V_4$). The last equilibrium position occurs at $x_n=1/3$. After pull-in the structure will stop at the designed stopper position (in this example in the middle of the initial gap), where the electrostatic force is equal to the sum of the mechanical force with the reaction force of the stopper.

When reducing the voltage applied, we would like the system to return to the same stable position taken at the threshold of pull-in, but that is not the case. Rather, after pull-in the electrostatic force increases as the gap decreases ($F_e(V_4;0.5)$ in Fig. 2). Because the electrostatic force is now larger than it was when it collapsed, a lower voltage is required to reach balance between the electrostatic and mechanical force ($F_p(V_4;0.5)$ in Fig. 2). There are two distinct solutions for the position where the mechanical force equilibrates the electrostatic force (the reaction of the stopper becomes zero). As the higher displacement solution is an unstable position, the structure returns to the stable zero position. Consequently, the hysteresis depends on the stop position. Designing a structure with a stop position closer to the deflection at pull-in results on a smaller value of the hysteresis. Therefore if we can calculate the hysteresis and the pull-in value from device dimensions, we can fully analytically describe the static behavior of the structure.

The values predicted for the release voltages by the 2D hysteresis model derived are presented in Figure 3. The predicted release voltages are at 8.7V and 9.4V for the asymmetric and symmetric drive respectively.

![Fig. 2: Explaining hysteresis.](image)

**DEVICE FABRICATION**

A modification on surface micromachining, a so-called epi-poly process [6], was used for the fabrication of 11 µm thick single-side clamped 100 µm long free-standing test structures with electrodes (Fig. 4). The deflection can be 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 placed directly underneath the axial direction of the non-deflected beam. Finally, there are electrically isolated stoppers to limit the lateral motion.

**EXPERIMENTAL RESULTS**

The first results are presented in Fig. 5 for both modes of operation. As expected, the asymmetric drive presents a parabolic change on the capacitance, until the pull-in is reached. The symmetric case presents a much sharper transition at pull-in. The measured pull-in voltage, for the asymmetric actuation, was about 9.1V, which is near the predicted value from modeling ($V_{pi}=9.6$ V). The difference is mainly due to the simplifying assumptions used, the process tolerances and uncertainties in the value of the Young’s modulus used in the numerical computation.

For symmetric actuation, the measured value was about 11 V, and showed a relatively large sample-to-sample deviation. The larger deviation of measurements to theoretical prediction, and the larger spreading in pull-in values, indicates a larger dependency on variations in the dimensions due to tolerances caused by the fabrication techniques. As mentioned, this is due to the fact that in symmetric drive, a difference in electrostatic forces is balanced by the spring force, whereas an electrostatic force is directly balanced in the asymmetric mode of operation.

Figure 6 presents the behavior of a sample over a complete cycle (with increasing and decreasing voltage) for the two actuations being studied. When comparing the results with those obtained from the modeling (Fig. 3), a reasonable agreement is observed. For the asymmetric case we have a measured hysteresis gap of about 1V, which is in agreement with the model. The small shift in position is mainly due to the simplifications in the model.

For the symmetric case, the release voltage is in close agreement with the model. However, the pull-in takes place at a voltage level lower than expected, due to the high sensitivity to tolerances mentioned before. At pull-in, the structure deflects to a position where the electric force is in equilibrium with the sum of the mechanical force and the reaction force on the stopper. Because of this new equilibrium situation, the small imperfections, that do give a significant contribution to the pull-in, do not affect the release voltage. Actually, the release voltage is closer to the model value as compared to the asymmetric case, because the non-idealities (stray capacitances, fringe fields) that are not considered in the model tend to cancel out in the symmetric device.

The pull-in of a selected beam has also been measured over a period of time asymmetrically actuated. Figure 7 shows the pull-in voltage over 26 days. There seems to be a major source of drift during the first 10 days (about -1.2 mV/day) and stabilization afterwards. The temperature coefficient was calculated from temperature data taken simultaneously and indicates a TC of -1mV/K. This is mainly due to beam elongation and the temperature dependence of the modulus of elasticity, and is in agreement with

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**Fig. 4:** photograph of the single-side clamped structure.

**Fig. 5:** Experimental results a) asymmetric and b) symmetric actuation.
simulations. The initial drift is expected to be due to charging of a dielectric layer between the electrodes [7]. We suspect a polymer to be deposited on the sidewall during plasma etching to be responsible.

**Fig. 6:** Measured pull-in and release voltages over a cycle for a) asymmetric and b) symmetric drive.

**CONCLUSIONS**

For proper operation of this structure as a voltage reference, the pull-in should be as abrupt as possible and the effect should be reproducible. As shown, the asymmetric drive performs much better with respect to pull-in voltage reproducibility, while the symmetric drive has a better defined threshold. The key performance parameter that leads to the selection of either type is strongly application dependent. For use as a dc reference, where stability and device-to-device reproducibility is crucial, the asymmetric case seems to offer superior operational performance as compared to the symmetric one.

Although the symmetric drive seems not to be the best choice to operate the device, it can be used as good indicator of the tolerances and imperfections in a surface micromachining process. Its actuation characteristics 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.

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**REFERENCES**