Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Procedia Chemistry 1 (2009) 1387–1390

Procedia Chemistry

www.elsevier.com/locate/procedia

Proceedings of the Eurosensors XXIII conference

Temperature Sensitivity of Silicon Cantilevers with the Pull-in Instability Method

Hamed Sadeghian[a,b,]*, Chung-Kai Yang[a], Johannes F. L. Goosen[b], Andre bossche[a], Paddy J. French[a], Fred van Keulen[b]

[a]*Electronic Instrumentation Laboratory, Delft University of Technology, Delft 2628 CD, The Netherlands*
[b]*Department of Precision and Microsystems Engineering, Delft University of Technology, Delft 2628 CD, The Netherlands*

Abstract

In this paper the temperature effects on [110] Silicon cantilevers is analyzed and measured in the range of 25 -100 °C. The quasi-static electrostatic pull-in instability method developed recently for ultra-thin cantilevers ["Characterizing Size-dependent Effective Elastic Modulus of Silicon Nanocantilevers Using Electrostatic Pull-in Instability", Applied Physics Letters, Vol. 94(22), p. 221903, 2009] is employed to measure the temperature sensitivity of ultra-thin cantilevers. A temperature sensitivity of 81.3 °C/V is obtained. The temperature sensitivity is mostly due to the temperature dependence of the effective Young's Modulus of silicon. It is shown that changes in geometrical dimensions due to the change in temperature can be neglected. The changes in the effective Young's Modulus due to the changes in temperature are extracted using an electromechanical-coupled system. The pull-in method showed substantial advantages over other methods used for the study of the thermal effects on micron and sub-micron structures. The results demonstrate a new concept for a temperature sensor with ultra high sensitivity.

Keywords: Temperature sensitivity; Pull-in instability; Cantilever; Nanoelectromechanical systems

1. Introduction

Silicon cantilevers have attracted considerable interest, compared to quartz crystal resonators, in the last few years. They are demonstrated to be extremely sensitive mass [1], force [2] and displacement sensors [3]. However, the ultra-sensitivity of these structures, and specifically silicon cantilevers, also makes them sensitive to other effects. One of the significant effects is the environmental temperature. As evidence, the force sensitivity of silicon cantilevers is determined by $T^{1/2}$, in which T is the temperature [2]. It has been shown that the inherent temperature sensitivity of silicon over the range of -45 to 85 °C is more than 20 times greater than that of the lowest-grade quartz crystal oscillators [4]. The temperature sensitivity in the silicon cantilevers is mostly due to temperature dependence of the elastic modulus. It has been shown that the thermal coefficient of the elastic constant in silicon is negative [4, 5], thus increasing the temperature would cause a softening effect of the material. Recently, most of the research on ultrasensitive mass or force sensing has been done in a controlled low temperature condition, in order to reduce the noise of the systems [1,2] and to avoid the temperature induced stiffness changes. However,s this temperature sensitivity can also be used as a temperature sensing principle, provided that the softening of the cantilever can be quantitatively measured. In this paper, we investigate the temperature sensitivity of sub-micron silicon cantilevers using the electrostatic pull-in instability method [6]. Since the voltage can be easily and accurately measured in the method (e.g. µV), the small change due to temperature change can be captured. The paper is organized as follows; the first part describes the fabrication of sub-micron cantilevers, the measurement method and experimental results. The second part, the change in the effective Young's Modulus, $\tilde{E}$, is extracted, which is linked to the changes in temperature.

---

* Corresponding author. Tel.: +31-152782703; fax: +31-152785755.
E-mail address: H.SadeghianMarnani@tudelft.nl

1876-6196/09
doi:10.1016/j.proche.2009.07.346

2. Fabrication and Experimental Measurements

2.1. Fabrication of sub-micron silicon cantilevers

Silicon cantilevers are fabricated from (100) smartcut® silicon-on-insulator wafers with a 1 μm buried oxide and a 340 nm silicon device layer. The thickness of the SOI wafer is determined by ellipsometric measurements fitted with a multi-layer model. Cantilevers were patterned by standard photolithography followed by SF_6 plasma etching. The patterned structures were underetched in HF solution and dried using the critical point drying technique. The width of the cantilevers is 8 μm and the lengths range from 8 to 100 μm. Figure 1 shows a SEM picture of the 340 nm thick fabricated cantilevers.

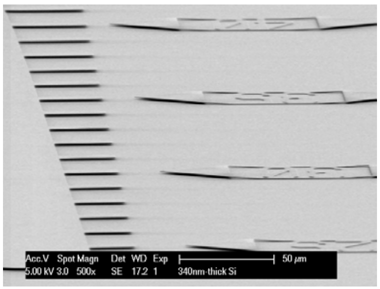


Fig. 1. SEM of 340 nm thick cantilevers with different lengths.

2.2. Electrostatic pull-in instability measurement

This method makes use of variations in the electrostatic pull-in instability [6] of a cantilever. By applying voltage between the cantilever and the substrate, the electrostatic force deflects the cantilever, as shown schematically in figure 2(a). The electrostatic force is approximately proportional to the inverse of the square of the gap between the cantilever and the substrate. When the voltage exceeds the critical voltage, called the pull-in voltage, the cantilever is suddenly pulled into the substrate. Figure 2(b) shows a SEM image of a cantilever pulled into the substrate. The measurement setup, used in this work consists of a voltage source, a semiconductor testing probe station and a microscope. The cantilevers are heated up from 25 to 100 °C by a temperature controlled chuck in an enclosed compartment. The voltage is gradually increased and visual observation of the substantial color change, shown as an example in figure 2(c), is used to determine the pull-in instability point.

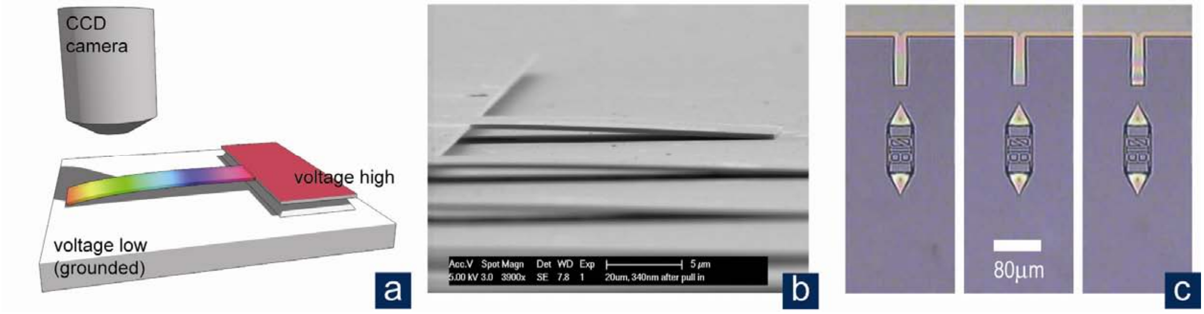
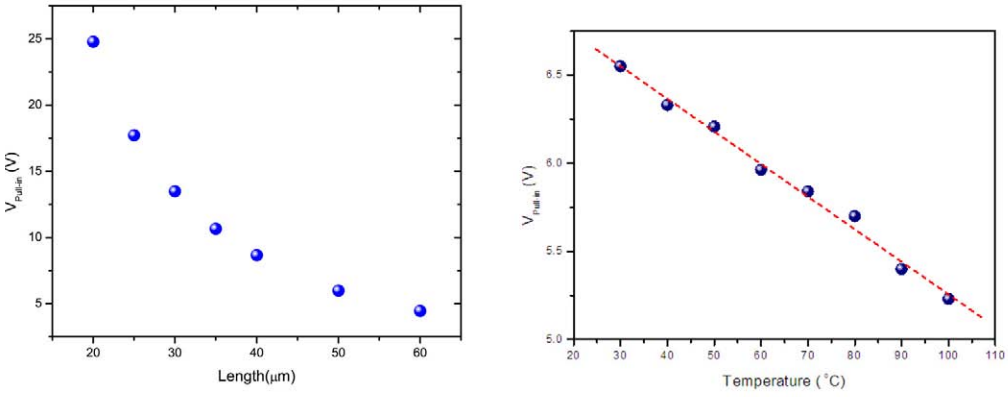


Fig. 2. (a) Schematic of the measurement setup and the cantilever. (b) SEM of the cantilevers pulled-in to the substrate. (c) Micrograph of the pull-in measurement, at initial, half way and after pull-in (left to right) of a 80 μm long cantilever.

2.3. Electrostatic pull-in instability vs. temperature

The measurement of the pull-in voltage is repeated for cantilevers of different lengths and for each controlled temperature. Figure 3(a) shows the pull-in voltage versus different lengths of 340 nm thick silicon cantilevers, the measured inverse relationship is validated by the theoretical values calculated from [9] and the error is about 3%, which shows the accuracy of the measurement. Figure 3(b) presents the measured pull-in voltage versus temperature of a 50 µm long cantilever, the error of the measurement is mainly attributed to the temperature uncertainty of the thermal chuck used. Increasing the temperature decreases the pull-in voltage. This is due to both elongation of the cantilever's length and softening of the material by decreasing the $\tilde{E}$. However, it has been reported that relative changes of the geometrical dimensions are less than 0.5% [2], therefore the change of $\tilde{E}$ in relation to the temperature is the main reason for the change in the pull-in voltage. A temperature sensitivity of 81.3 °C/V is found from figure 3(b). Since the voltage can be precisely applied and consequently the pull-in voltage can be measured very accurately, e.g. with an accuracy of µV, a µ-Celsius temperature sensor resolution can be achievable.



(a) (b)

Fig. 3. (a) Pull-in voltage versus length of the 340 nm thick cantilever, (b) shifts in the pull-in voltage of a 50 µm long cantilever.

3. Temperature effects on the effective Young's Modulus

The cantilever is modeled using Euler-Bernoulli beam theory with a constant cross-sectional area along the length of the beam. The nonlinear electromechanical-coupled differential equation for a cantilever, enhanced with a first-order fringing correction is presented as [7]:

$$\tilde{E}I\frac{d^4w}{dx^4}=\frac{\varepsilon_0 V^2 b}{2[g-w(x)]^2}\left(1+0.65\frac{g-w(x)}{b}\right), \tag{1}$$

The corresponding boundary conditions for a cantilever state as

$$w(0)=0,\qquad \left.\frac{dw}{dx}\right|_{x=0}=0,\qquad \left.\frac{d^2w}{dx^2}\right|_{x=L}=0,\qquad \left.\frac{d^3w}{dx^3}\right|_{x=L}=0\,, \tag{2}$$

where $\tilde{E}$ is the effective Young's Modulus, I is the effective moment of inertia of the cross-section, w is the deflection of the cantilever, ε_0 is the permittivity of air, V is the applied voltage, b the width of the cantilever, and g is the initial gap between the cantilever and the substrate.

The temperature induced-shifts in the pull-in voltages of silicon cantilevers are mostly due to the temperature dependence of the elastic modulus. Therefore, the changes in the $\tilde{E}$ can be determined from the shifts in the pull-in voltage. The pull-in voltage shifts of a cantilever due to temperature can be approximately determined as

$$\frac{\Delta V}{V}=\frac{1}{2}\frac{\Delta\tilde{E}}{\tilde{E}}-2\alpha\Delta T \tag{2}$$

where α is the thermal expansion coefficient which is approximately $2.59\times10^{-6}\ K^{-1}$ [8] and ΔT is the change in the temperature. Using equation (2), one can calculate the changes in the $\tilde{E}$ with known temperature and pull-in voltage changes. By doing so, the

$\Delta\tilde{E}/\tilde{E}$ is about -0.778% per °C. The change of pull-in voltage due to the change in geometrical dimensions is about 0.00518%, this is in agreement with the previous reporting [2] and is considered to be negligible compared to the Ẽ change..

4. Conclusions

In conclusion, we studied the temperature sensitivity of silicon sub-micron cantilevers using the quasistatic electrostatic pull-in instability. Increasing temperature caused a decrease in the pull-in voltage. This decrease was mostly due to the influence of the temperature on the effective Young's Modulus of silicon and consequently softening of the cantilever. A temperature sensitivity of 81.3 μ °C/μV was achieved, indicating that sub-micron silicon cantilevers with the quasistatic pull-in instability method show a promising concept for a new type of ultra-sensitive temperature sensor.

Acknowledgements

This work was financially supported by the Dutch national research program on micro technology, MicroNed (Project code: IV-C-2) and NanoNed (Project code: TQVB46).

References

1. Yang YT, Callegari C, Feng XL, Ekinci KL, Roukes ML. Zeptogram-Scale Nanomechanical Mass Sensing. Nano Lett. 2006; **6(4)**, 583-586.
2. Gysin U, Rast S, Ruff R, Meyer E, Lee DW, Vettiger P, Gerber C. Temperature dependence of the force sensitivity of silicon cantilevers**.** Phys. Rev. B. 2004; **69(4)**, 045403.
3. Naik A, Buu O, Lahaye MD, Armour AD, Clerk AA, Blencowe MP, Schwab CK. Cooling a nanomechanical resonator with quantum back-action. Nature. 2006;**443**, 193-196.
4. Melamud R, Kim B, Chandorkar SA, Hopcroft MA, Agarwal M, Jha CM, Kenny TW. Temperature-compensated high-stability silicon resonators. Appl. Phys. Lett. 2007; **90**, 244107.
5. McSkimin HJ. Measurement of Elastic Constants at Low Temperatures by Means of Ultrasonic Waves-Data for Silicon and Germanium Single Crystals, and for Fused Silica. J. Appl. Phys. 1953;**24**, 988.
6. Sadeghian H, Yang CK, Goosen JFL, van der Drift E, Bossche A, French A, van Keulen F. Characterizing size-dependent effective elastic modulus of silicon nanocantilevers using electrostatic pull-in instabilit. Appl. Phys. Lett. 2009;**94(22)**, 221903.
7. Sadeghian H, Rezazadeh G, Osterberg PM. Application of the Generalized Differential Quadrature Method to the Study of Pull-in Phenomena of MEMS Switches. J. Microelectromech. Syst. 2007;**16**, 1334.
8. Watanabe H, Yamada N, and Okaji M. Linear Thermal Expansion Coefficient of Silicon from 293 to 1000 K. International Journal of Thermophysics, 2004. **25**(1), 221.
9. Rezazadeh G, A comprehensive model to study nonlinear behavior of multilayered micro beam switches. Microsystem Technologies, 2008. 14(1), 135