Proceedings of the 4th International Conference on Nanostructures (ICNS4)
12-14 March, 2012, Kish Island, I.R. Iran

The Thermal Effect on Pull-in Instability of Electrostatically Actuated Nanoswitches

Anooshiravan. Farshidianfar[a]*, Ali. A. Ghassabi[a], Fatemeh. Tavakolian[b]

[a] Department of Mechanical Engineering, Ferdowsi University of Mashhad, 9177948944, Iran
[b] Department of Engineering, Khayyam Higher Education Institute, 9177948944, Iran
*farshid@um.ac.ir

Abstract: In this study, based on continuum mechanics, an Euler–Bernoulli model has been applied to analyze the pull-in instability of nanocantilever switch by consideration of thermal effects. The effects of initial gap, length of the nanoswitch and temperature change are studied on the pull-in voltage. Results are demonstrated for the dependence of pull-in voltage on the length of the nanoswitch as well as temperature change. It is concluded that the effect of temperature change on the instability of nanoswitch is significant. Interesting results are obtained, which are helpful in the modeling or designing process of a nanoswitch.

Keywords: Nanoswitch; Euler-Bernoulli model; Pull-in instability; Pull-in voltage; Temperature change

Introduction

Beam-type electrostatic actuators have become one of the common components in constructing micro/nano-electromechanical system (MEMS/NEMS) [1-2]. Nanomechanical switches are important building blocks for the design of NEMS applications, such as nanotweezers and some other nanoscale actuators [3]. However, there is an inherent instability, known as the pull-in phenomenon, in NEMS switches.

Consider a beam-type actuator constructed from a conductive electrode suspended over a conductive substrate. Applying voltage difference between an electrode and ground causes the electrode to deflect towards the ground. At a critical voltage, which is known as pull-in voltage, the electrode becomes unstable and pulls-in on to the substrate.

The first issue that appears at the nanoscale is the effect of dispersion forces such as Casimir attraction. At small separations (typically less than several micrometers), the Casimir force can highly influence the instability of NEMS. These forces can be explained by electromagnetic quantum vacuum fluctuations existing between two separated plates [4]. In this case, the interaction between the two surfaces is described by the Casimir force. Some researchers have studied the pull-in behaviour of electromechanical systems having considered the effect of the Casimir force but without considering of thermal effects [5-8].

A one degree of freedom lumped parameter model has been proposed by Lin and Zhao [5, 6] to survey stiction of nanoswitch in the presence of electrostatic and Casimir attractions. Ramezani *et al.* [7] used Green’s function to investigate the pull-in parameters of nanocantilever beam type actuators under Casimir forces.

It is noted from [9, 10] that the operating temperature of the flexible part of a MEMS and NEMS device can be changed. Any change in the operating temperature of the flexible part, cause the coupled behaviour of the MEMS and NEMS device varies because the stress state is altered. Therefore, a full thermo-electro-mechanical analysis is required in identifying pull-in voltage. Several researchers have studied the effects of temperature variations on the performance of microbeam-based MEMS, particularly microswitches [11-13], but there are not any similar investigations for nanoswitch.

However, to the best of our knowledge, no investigation has been performed on pull-in instability of nanoswitch. In this study, for the first time, Thermal-Euler-Bernoulli model has been applied to analyse the pull-in instability of a nanocantilever switch. The effects of temperature variations, length of the beam and initial gap on the pull-in instability of the nanoswitch are considered in detail.

Modeling

Figure 1 shows a typical nano-switch that consists of a fixed electrode and a nano-beam of length L, width w and thickness h, separated by a dielectric spacer with an initial gap g.

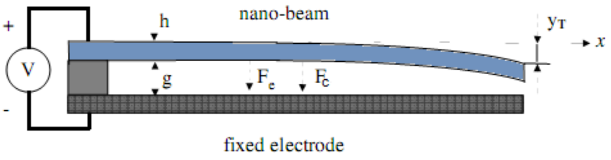

Figure 1. Beam model of a nano-switch

To investigate the pull-in parameters of the switch, we are only interested in static deflection of the beam. Therefore, the governing equation using Euler-Bernoulli model maybe written as

$$EI\frac{d^4y}{dx^4} - N_t\frac{d^2y}{dx^2} = F_e + F_c \qquad (1)$$

Where y is the deflection of the beam, x is the position a long the beam measured from the clamped end, $I = wh^3/12$ is the moment of inertia of the beam cross section, and E is the young modulus, N_t is the constant axial force associated with thermal effect, F_e and F_c are the electrostatic and Casimir forces per unit length of the beam, respectively. It is noted that the equation for nanoswitch without thermal effect has been obtained before in [7].

Considering the first order fringing field correction [14], the electrostatic force per unit length of the beam is

$$F_e = \frac{\varepsilon_0 w V^2}{2(g-y)^2}\left(1 + 0.65\frac{g-y}{w}\right) \qquad (2)$$

Where $\varepsilon_0 = 8.854 \times 10^{-12}\ C^2 N^{-1} m^{-2}$ is the permittivity of vacuum and V is the applied voltage.

The Casimir force per unit length of the beam is [15]

$$F_c = \frac{\pi^2 \bar{h} c w}{240(g-y)^4} \qquad (3)$$

Where $\bar{h} = 1.055 \times 10^{-34}\ Js$ is Planck's constant divided by 2π and $c = 2.998 \times 10^8\ ms^{-1}$ is the speed of light.

On the basis of the theory of thermal elasticity mechanics, the axial force Nt can be written as [16]

$$N_t = -\frac{EA}{1-2\nu}\alpha_x T \qquad (4)$$

Where α_x denotes the coefficient of thermal expansion in the direction of the x-axis, ν is Poisson's ratio, A is cross section of the beam, and T is temperature change.

For convenience, the model is formulated in the non-dimensional form. Substituting Eqs. (2) – (4) into (1) and introducing the non-dimensional variables

$$u = y/g,\ z = x/L \qquad (5)$$

The following non-dimensional equation is obtained

$$\frac{d^4u}{dz^4} + N_t{}^* \frac{d^2u}{dz^2} = F(z) = \frac{R_c}{[1-u(z)]^4} + \frac{\beta}{[1-u(z)]^2} + f\frac{\beta}{[1-u(z)]} \qquad (6)$$

The non-dimensional parameters appearing in Eq. (6) are

$$R_c = \frac{\pi^2 \bar{h} c w L^4}{240 g^5 EI},\ \beta = \frac{\varepsilon_0 w V^2 L^4}{2g^3 EI},\ f = 0.65\frac{g}{w},\ N^*{}_t = \frac{A\alpha_x T L^2}{(1-2\nu)I} \quad (7)$$

And the associated boundary conditions are

$$u(0) = \frac{du(0)}{dz} = \frac{d^2u(1)}{dz^2} = \frac{d^3u(1)}{dz^3} = 0 \qquad (8)$$

Due to the nonlinearity of the distributed lateral load $F(z)$ acting on the nano-beam, an exact solution of Eq. (6) is almost impossible. To simplify the analysis and yet achieve sufficient accuracy, a linear distributed load (LDL) model is proposed by Yang *et al.* [8] which approximately treat the distributed lateral load as a linear function of z.

Using a similar method to the one described in [8], the pull-in voltage can be obtained for nanocantilever switch.

Results and Discussion

Based on the formulations obtained with the Thermal-Euler-Bernoulli model, the pull-in properties of nanoswitch are discussed here. Our objective is to investigate the effect of the temperature variations on the pull-in instability of nanoswitch.

In order to evaluate the validity of the present method, results were compared with those given in the literature. A cantilever switch with L=200 nm, h=3.5nm, E=166GPa, w=30nm was considered. In Table 1 pull-in voltages obtained by the LDL are compared to those given by [6, 7]. The thermal effect is not considered in this case. As can be observed, the present results are quite close to those predicted by [6] because the present analysis is based on the distributed parameter model as well.

Table 1. Pull-in voltages (in V) obtained by the LDL compared with previous studies.

g/w	[7]	[6]	Present
0.9	0.8944	1.2329	1.2208
1.0	1.1705	1.5309	1.4407
1.1	1.4162	1.8093	1.7168

Now, let us consider the influence of the initial gap on the pull-in voltage. The maximum deflection of the nanoswitch versus applied voltage is shown in Figure 2 for different values of initial gap. According to this figure, as the initial gap decreases, the pull-in voltage decreases. As a result, by decreasing the initial gap, the nanoswitch becomes more unstable.

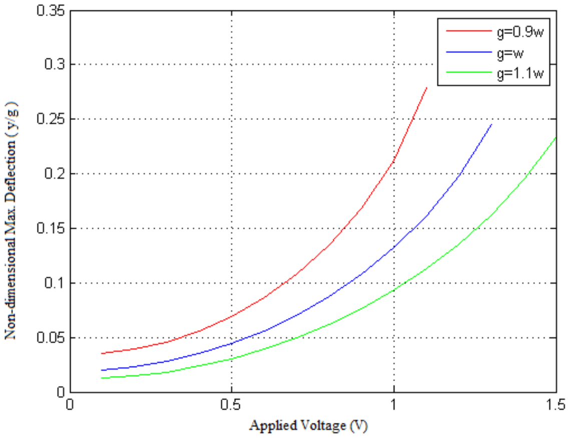

Figure 2. Non-dimensional maximum deflection versus applied voltage for different initial gaps.

We next present the results for the thermal effect on the pull-in voltage of the silicon nano-beam with $\alpha_x = 2.6 \times 10^{-6} K^{-1}$ and $\nu = 0.06$ [17]. The results are shown in Figure 3. This figure shows the variations of the pull-in voltages with the temperature for various initial gaps. It is observed that, as the temperature increases, the pull-in voltage is reduced.

The presence of temperature change is to decrease pull-in voltage. It is found that the pull-in voltage for the nanoswitch including the thermal effect is much lower than that without considering the change of temperature. As a result, by increasing the temperature, the nanoswitch becomes more unstable. Also the pull-in voltage increases with the increase of initial gap.

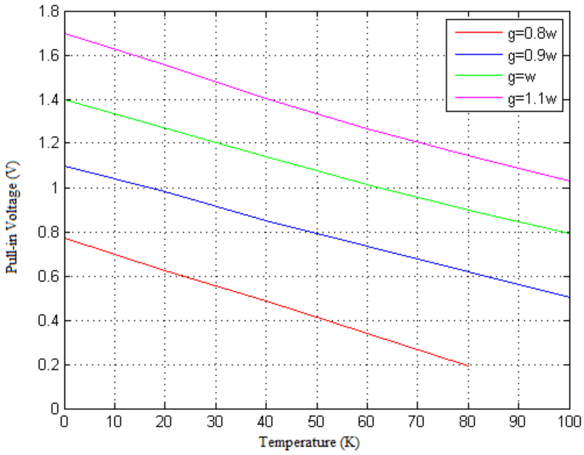

Figure 3. Pull-in voltage versus temperature for different values of initial gap.

Figure 4 shows the variations of the pull-in voltages with the temperature for various nanoswitch's lengths. According to this figure, with increasing temperature, as the length of the nanoswitch increases, the pull-in voltage decreases. In long lengths, the temperature effect on the pull-in voltage is higher than short lengths. So a nanoswitch with length of more than **10w**, quickly becomes unstable.

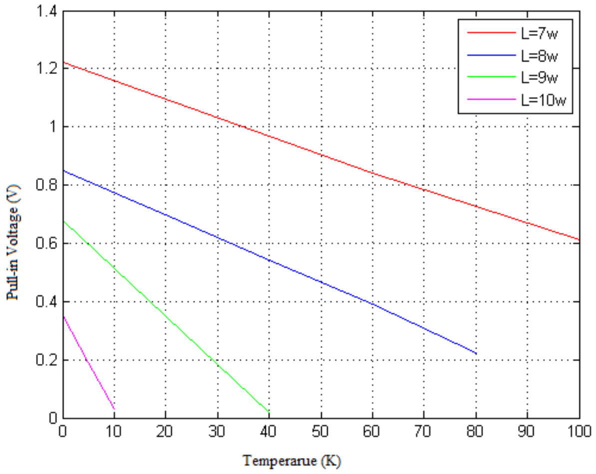

Figure 4. Pull-in voltage versus temperature for various nanoswitch's lengths.

Conclusions

On the basis of the theory of thermal elasticity mechanics, an Euler - Bernoulli model is developed for pull-in instability of nanocantilever switch, which takes into account the effect of temperature change in the formulation.

The influence of temperature change on the pull-in instability of nanoswitch is discussed. It can be concluded that, the pull-in voltage decreases with increasing the temperature. As a result, in constructing NEMS, we must use a nanoswitch with the length of lower than 10w.

References

[1] L. Zhang, S. V. Golod, E. Deckardt, V. Prinz, D. Grutzmacher, "Free-standing", Physica E 23 (2004) 280.

[2] C. H. Ke, H. D. Espinosa, "Nanoelectromechanical systems (NEMS) and modeling", in: M. Rieth, W. Schommers, P. D. Gennes (Eds.), "Handbook of Theoretical and Computational Nanotechnology", 2006, Chapter121, American Scientific Publishers, Valencia.

[3] P. Kim, C. M. Lieber, "Nanotube nanotweezers" Science, 286 (1999) 2148–2150.

[4] G. L. Klimchitskaya, U. Mohideen, V. M. Mostepanenko, Phys. Rev. A, 61(2000) 062107.

[5] W. H. Lin, Y. P. Zhao, "Casimir effect on the pull-in parameters of nanometer switches", Microsystem. Technologies, 11 (2005) 80–85.

[6] W. H. Lin, Y. P. Zhao, "Nonlinear behaviour for nanoscale electrostatic actuators with Casimir force", Chaos Solitons and Fractals, 23 (2005) 1777–1785.

[7] A. Ramezani, A. Alasty, J. Akbari, "Closed-form solutions of the pull-in instability in nano-cantilevers under electrostatic and inter molecular surface forces", Int. J. Solids Struct, 44 (2007) 4925–4941.

[8] J.Yang, X. L. Jia, S. Kitipornchai, "Pull-in instability of nano-switches using nonlocal elasticity theory", J. Phys. D: Appl. Phys, 41 (2008) 035103.

[9] C. Zener, "Internal friction in solids. I. Theory of internal friction in reeds", Phys. Rev, 52 (1937) 230.

[10] C. Zener, "Internal friction in solids. II. General theory of thermoelastic internal friction", Phys. Rev, 53 (1938) 90.

[11] B. D. Jensen, K. Saitou, J. L. Volakis, K. Kurabayashi, "Fully integrated electro-thermal multi domain modeling of RF MEMS switches", IEEE Microw Wirel Compon Lett, 13 (2003)364.

[12] Y. Zhu, H. D. Espinosa, "Reliability of capacitive RF MEMS switches at high and low temperatures", Int. J. RF. Microw, 14 (2004) 317.

[13] Y. Zhu, H. D. Espinosa, "Effect of temperature on capacitive RF MEMS switch performance – a coupled field analysis", J. Micromech. Microeng, 14 (2004) 1270.

[14] J. M. Haung, K. M. Liew, C. H. Wong, S. Rajendran, M. J. Tan, A. K. Liu, "Mechanical design and optimization of capacitive micromachined switch", Sensors and Actuators A, 1993 (2001) 273.

[15] S. K. Lamoreaux, "The Casimir force background, experiments, and applications", Reports on Progress in Physics, 68 (2005) 201.

[16] A. D. Kovalenko, "Thermoelasticity", 1969, Wolters-Noordhoff Publishing, Gröningen, Netherlands.

[17] O. Francais, I. Dufour, "Normalized abacus for the global behaviour of diaphragm: pneumatic, electrostatic, piezoelectric or electromagnetic actuation", J. Model. Simul. Microsyst, 2 (1999) 149.