Temperature effect on pull-off force for gold cantilevers array

C Birleanu¹, M Pustan¹, F Serdean¹, V Merie² and S Craciun¹

¹ Department of Mechanical Systems Engineering, Micro and Nano Systems Laboratory, Technical University of Cluj-Napoca, Cluj-Napoca, Romania
² Department of Materials Science and Engineering, Micro and Nano Systems Laboratory, Technical University of Cluj-Napoca, Cluj-Napoca, Romania

Abstract. This paper focuses on revealing the length influence of a group of gold cantilevers on the mechanical behaviour (i.e. bending stiffness, Young modulus, pull-off force) on the one hand and on the investigation of the temperature influence on the pull-off force of thermally actuated microcantilevers, on the other hand. The length was ranged between 200 µm and 350 µm while the temperature was ranged between 20 °C to 100 °C. The tests were performed using an atomic force microscope. The results obtained in the study are important to enhance the design of MEMS devices and to increase their reliability and their lifetime.

1. Introduction
When designing a micro or nano mechanic device, an important challenge is to analyse the interaction between contacting bodies within the system. Because of the very small size of microelectromechanical systems (MEMS), these surface forces could become prevalent and may prevent reliable operation of the device.

Due to the large surface area to volume ratio of MEMS, surface effects such as electrostatics and wetting dominate over volume effects as inertia or thermal mass [1, 2].

Micro and nano cantilevers, a major breakthrough in sensors, have been employed for physical, chemical and biological sensing. The major advantages of employing microcantilevers as sensing mechanisms over the conventional sensors include their high sensitivity, low cost, they are performed through the simple procedure and due to the quick response and low power requirement [3]. For micro cantilevers used as actuators, the thermal actuation method has some benefits over other methods. They can detect heat changes with attojoule sensitivity [3, 4]. Thus cantilever is used as a tool to evaluate the change of stress occurring in the material of the cantilever, caused for example by changes in temperature.

A contact between two surfaces, or a substrate and a sensor generates adhesion forces. The force required to separate two surfaces is commonly called “pull-off”. Behaviours of the microparts in contact require deep knowledge to succeed in micro-assembly operations [5].

In this paper our work focuses on experimentally determining the mechanical and tribological characteristics of micro-components, such as microcantilever. The experimental tests were carried out on microcantilevers of different sizes and in different temperature conditions using an atomic force microscope (AFM).

2. Materials and Methods
2.1. Investigated samples
For the investigated samples the basic actuation designs are considered. These consist of suspended gold cantilevers with different geometrical dimensions, as shown in the insets of figure 1. The Young’s modulus taken into consideration is \( E = 80 \text{ GPa} \). The microstructures were made in 10
lithography and deposition steps using a wafer substrate of silicon, with a gap \( g_0 \) between flexible part and substrate of about 3 \( \mu m \) (figure 2). The dimensions of the flexible part are: the length \( l_0 \) at ambient temperature \( l_0 = 200, 250, 300, \) and 350 \( \mu m \); the width of the cantilever \( w_0 = 35 \mu m \) and the cantilever thickness \( t_0 = 2 \mu m \). The beam anchor is a cuboid with two sides of 110 \( \mu m \) and a thickness of 4 \( \mu m \).

The sketch of a constant rectangular cross-section microcantilever is shown in figure 2. The microcantilever is thermally actuated and subjected to bending stress on \( z \) direction (\( \Delta z \) is the bending displacement of the microcantilever free-end). Because the dimensions of the beam, \( w_0 \) and \( t_0 \), are sufficiently small compared to the length \( l_0 \), we consider the usual Euler-Bernoulli assumption [5].

We consider a microcantilever which is subject to a bending stress and integrating a thermal effect due to the change in test temperature. The stiffness of the cantilever subjected to temperature can be written as [6]:

\[
 k_z = \frac{E \cdot w_0 \cdot t_0^3 (1 + \alpha \Delta T)}{4l_0^2}
\]

where \( k_z \) is the cantilever stiffness in \( z \) direction, \( E \) is the Young’s modulus of the microcantilever material, \( \alpha \) is the thermal expansion coefficient and \( \Delta T \) is the temperature variation. In this work we will use a constant value of the linear coefficient of thermal expansion whose value is one third of the volumetric coefficient of thermal expansion [5].

Under the force applied to the free end of the cantilever the incidental contact during testing cannot always be excluded. The applied load has an upper limit beyond which the mechanical restoring force of the microcantilever can no longer resist thereby leading to the collapse of the structure. This structural instability phenomenon is known as ‘pull-in’. An important role in adhesion plays the surface roughness. In this paper in order to analyse the temperature effect on the adhesion phenomenon, we assume that the contact surfaces are perfectly flat, so the actual contact area can be a large fraction of the apparent contact area between these microstructures.

2.2 Experimental procedure

The tests were performed at a range of temperature between 20\( ^\circ \)C - 100\( ^\circ \)C and at relative humidity (RH) of 40\% using the XE70 AFM. In addition to the topographical imaging, the AFM can also probe nanomechanical and other fundamental properties of sample surfaces, including their local adhesive or elastic properties.

The measurements with AFM were performed at controlled humidity conditions. This was conducted by placing the AFM in an environmental chamber having a controlled and adjustable air flow. Using a Peltier device, the measurements were performed over a range of processing temperatures between 20\( ^\circ \)C and 100\( ^\circ \)C and a contact time up to a few seconds. Each measurement was repeated many times in order to improve the accuracy of the experimental results.

The force of adhesion between microcantilevers and substrate was determined from the pull-off force measurements made with the AFM technique, based on the spectroscopy in point. The AFM tip was brought in contact with the upper surface of each cantilever in the free-end point and then bended to the substrate. The adhesion force was measured from the pull-off point on the force vs. distance curve. The cantilever used for investigation in contact mode is type HQ - NSC 35/Hard/Al BS with a nominal value of the spring constant \( k = 16 \) N/m and radius < 20 nm. In all experiments the bending force was applied to the free-end of the cantilever. The experimental data collected was imported into the XEI software. XEI is the AFM image processing and analysis program. Its powerful processing algorithms make analyses easy and streamlined.
3. Experimental investigations

Experimental investigations have begun by determining the real value of the elasticity module needed in analytical and numerical computation, nanoindentation of the cantilever material directly on anchor. The experimental values are interpreted using XEI software based on the Hertzian model. In ambient condition the effective Young’s modulus is 79.81 GPa, close value to the bulk Young’s modulus of gold (80 GPa) [7].

3.1 The influence of temperature on bending stiffness cantilever.

Stiffness of investigated cantilevers is experimentally determined based on force versus deflection of the tested specimens. The influence of temperature on stiffness was highlighted by changing the temperature within the range of 20–100 °C.

\[ k_{\text{analytical}} \approx k_{\text{experimental}} \]

Figure 3. Analytical and experimental bending stiffness versus samples length at 20 °C.

Figure 4. Experimental variation of the bending stiffness with temperature for samples

During AFM tests the vertical piezoelectric displacement of the scanning head \( z_{\text{piezo}} \) is controlled and the bending deflection of AFM probe is optically monitored. The bending deflection of cantilevers can be determined as:

\[ z_{\text{sample}} = z_{\text{piezo}} - z_{\text{AFM}} \] (2)

Slope of the load vs. displacement experimental curve provides the stiffness of the microcantilevers. Stiffness calculation based on equation (1) took into account only the out of plane deflection due to the mechanical force, thus from the total deflection was extracted the one due to temperature increase. A good correlation between the stiffness obtained based on analytical and experimental results at room temperature (20°C) are observed (figure 3).

The stiffness vs. temperature variation chart is presented in figure 4. In the stiffness vs. temperature variation chart (figure 4) it can be seen for all cantilevers a decrease in stiffness with increasing temperature. For all analysed samples, the rigidity obtained experimentally at bending decreases as the temperature drops by about 20%. For instance, at 20°C for the shortest cantilever the experimental stiffness is \( k = 0.77 \) N/m and at 100°C, \( k = 0.59 \) N/m. For the longest one at 20°C, \( k = 0.17 \) N/m and at 100°C, \( k = 0.12 \) N/m. The effect is due to the presence at higher temperatures of the thermal prestress considering that the anchor and the substrate are made of silicon that have a smaller thermal expansion coefficient than the gold cantilever.

3.2 Effect of temperature on adhesion

The adhesive effects between AFM probe (Si₃N₄) and microcantilever was determined based on the spectroscopy in point mode of AFM so-called force/distance measurements. The load applied for all measurements was 50 nN. Measurements were performed over a range of processing temperatures between 20°C and 100°C and a contact time up to a few seconds. All the experimental data collected was imported into the XEI image processing and analysis program. The pull-in and pull-off forces values are directly provided by the software. This measurement provides correct information about surface energy and adhesion only if the contact between AFM tip and cantilever surface remains in the elastic range. A statistical interpretation of the results was performed also for these data, calculating the dispersion values. The results are presented in figure 5.
Under ambient conditions, the reduction of the adhesion forces between the probe tip and microcantilever is limited by the existence of the meniscus force resulting from capillary condensation around the sites of contact between the tip and surface [8]. The maximum capillary force is acting when the surfaces are in contact [8]. However, once the temperature increases the effect of wet thin layer on the cantilever surface will decrease leading to lower adhesion force with temperature (figure 5). At the 20°C in environmental conditions (40%RH) for the cantilever with a length of 200 μm the experimentally adhesion force obtained is 14.3 nN and for a sample with a length of 350 μm the adhesion force obtained is 46.2 nN. At the 100°C the adhesion force for the shorter cantilever is 10.8 nN and for the longer one is 34.65 nN. Variability between the adhesion force measurements is expected, as represented by the bars on each data point (5 – 10%).

4. Discussion and conclusions
In this work two aspects were followed: the experimentally evaluation of the adhesion force when the temperature increases from 20°C to 100°C when a decrease of adhesion force with 20% - 25% was determined and then an evaluation of the length of microcantilever on adhesion when we have obtained an increase in the adhesion with increasing the length of cantilevers.

Deformation of the materials due to thermal effects can be used to actuate devices, forcing the increase of temperature in the device. Knowledge of the influence of temperature on mechanical properties of nanostructures it is essential for their use at the atomic scale which behaves qualitatively different at the nanoscale than at larger sizes. A random dispersion of the values of the pull-off force was observed within a single experiment of about ± 5-8% on gold surfaces cantilevers. This is attributed due to combinations of surface quality variations and imperfect balancing of the value of temperature. This was due to the fact that the samples tested clean surfacing became significantly contaminated by the air in the room during the time in which measurements were made.

The work confirms the view that, in determining the size of adhesion force between particles in the air and its dependence on temperature, particle size, roughness and surface chemistry are of crucial importance. In a study of force-distance curves obtained by, silicon AFM tips and gold cantilevers have provided useful data for real applications. The cantilever sensor field is exciting and dynamic. The limit for detection is constantly challenged and only the imagination sets the limit to new applications. Therefore the good understanding of the phenomena that occur to get a high-performance device is essential.

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