A MEMS Platform for Mechanical Testing of Soft Nanofibers and Nanowires

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1. Abstract

In this report, design, operation principles and finite elements analysis of a novel MEMS based mechanical testing platform for highly deformable nanofibers and nanowires is presented. Mechanical actuation is accomplished through a group of five thermal actuators by sequencing electrical inputs to a coordinated grip-release and pulling mechanism. This new actuation device is capable of generating tens of micronewtons force and total displacement of 100 μm. Unlike most surface micromachined MEMS actuators, such as nanotractors and scratch drives, the proposed platform is designed so that the force generated by the actuator does not decay with increasing travel length. Maintaining the applied force over large travel lengths is accomplished by separating the actuating and moving parts of the device. A leaf spring folded beam loadcell is implemented to measure the force on the sample. Primarily, this MEMS device is designed for mechanical characterization of electrospun polymer nanofibers.

2. Objective

The objective was to design a tension-testing platform with an on-chip actuator capable of relatively large travel and force range, tens of microns and micronewtons, respectively. This device is intended to be used to investigate the mechanical behavior of highly deformable nanowires, nanofibers and thin films. The forces required for such samples are typically in the range of 1-100 μN. The displacement required is 10-100 μm, depending on the sample length. The design of this actuator is such that the force generated by the actuator does not decay with travel length so that large deformations and large axial forces on the sample can be achieved.

3. Introduction

Because of the small dimensions of nanofibers and nanowires, MEMS devices provide a promising platform on which nanostructures can be mounted and tested. Such platform may incorporate on-chip load sensors such as leaf spring loadcells for high resolution force measurement. In order to apply force on the samples two types of actuation methods can be employed: on-chip actuation [T1,2,3] and external actuation [4]. The main advantages of on-chip actuators over external actuators are (a) better accuracy in aligning the sample with the loading direction in tensile loading, and (b) small size of the actuator which allows *in situ* tests inside scanning electron microscope (SEM) chambers for higher spatial resolution.

In this report, we present the operation principles and design steps of a MEMS mechanical testing platform designed to study the mechanical behavior of highly deformable 1D nanostructures. The deformation on the sample is applied using an

untethered shuttle actuated thermally, and load on the sample is measured using a folded leaf spring loadcell. The novelties in the current design are:

- A grip-pull-release mechanism achieves large deformations on the sample (~100 μm), and sustains the functionality of the actuator when stable large forces (a few tens of micronewtons) are needed while operating at low voltages. By this mechanism, large deformations can be obtained from a thermal actuator by translating an untethered shuttle. The actuator is a V-shaped thermal actuator, in which the unsupported length of the V-beams is reduced by lateral supports to increase the resistance of the actuator to buckling. *The inclusion of an unanchored-untethered element, which can be pulled freely by another actuator, is a direct consequence of the ability to use 4 structural polysilicon layers in the SUMMIT process, and planarization of layers 3 and 4.*
- A freestanding plate is incorporated in the gauge section of the tension test platform, on which the sample rests during sample mounting and SEM imaging after the tension tests. During tension tests, the plate is actuated electrostatically to separate form the sample, thus making the sample freestanding between the grips.

4. Description of Tension Test Platform

A schematic of the mechanical testing MEMS platform is shown in figure 1. A nanowire (sample) is mounted on the device with its two ends attached to the stationary and loading grips using a micro-manipulator with a sharpened probe [4]. Application of appropriately sequenced electrical inputs allows the thermal actuator to move the shuttle in the direction shown by the red arrow. Motion of the shuttle is transferred to the sample through the loadcell. The entire tension test is recorded optically. The deformation of the sample is calculated by measuring the motion of the loading grip. The force on the sample can be calculated by measuring the deformation of the loadcell.

The untethered shuttle with grip-release and pulling thermal actuators is designed to provide up to 100 μN force on the sample over 100 μm deformation. The principle of operation of the shuttle is described in section 5.

The loadcell, figure 1, consists of two pairs of folded beams. Its stiffness in this particular design is 2 N/m.

In order to facilitate sample manipulation during sample mounting and to provide a support for the broken halves of the sample after a tension test, e.g. collect them for *post mortem* SEM imaging, a suspended platform is designed (sample mounting/imaging platform) between the mounting grips. This platform is lowered during testing by applying a voltage between the substrate and the platform (figure 2). Finally, two grips are designed, as shown in figure 1 (loading grip and stationary grip) on which two sides of the nanowire are mounted. In this design, the sample is attached to the grips using high viscosity epoxy adhesive [4].

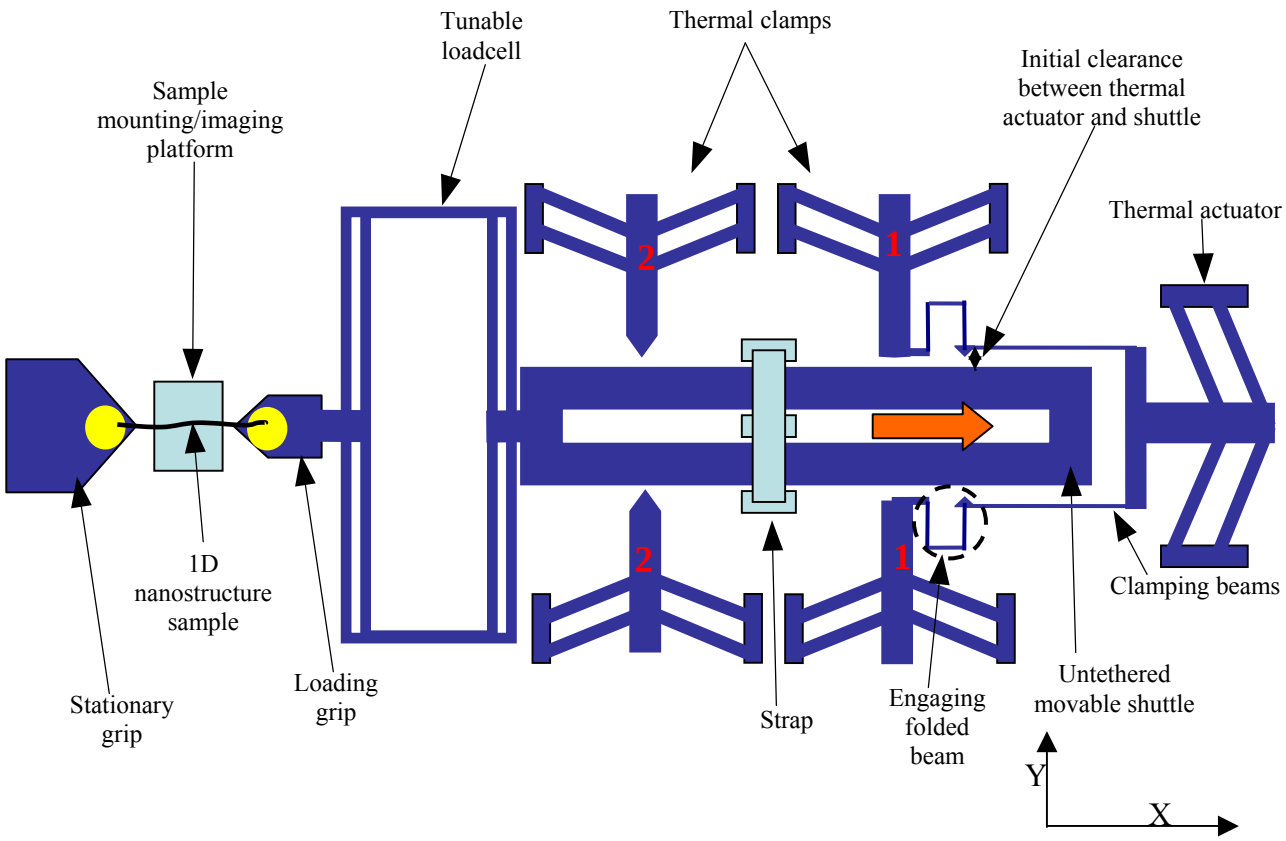

Figure 1. Schematic of the MEMS tensile testing device

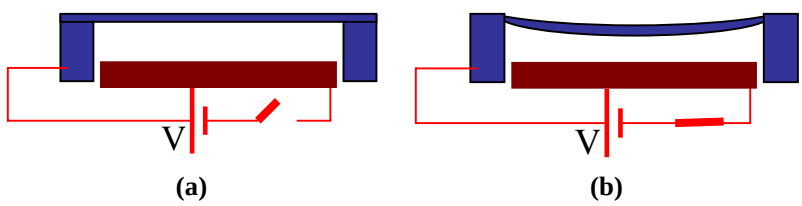

Figure 2. Side view of sample mounting/imaging platform **a)** before and **b)** during the actuation

5. Principle of Operation of the Actuator

The motion of the shuttle is due to the pulling action of the thermal actuator shown in figure 1. To pull the shuttle by the thermal actuator, first pair #1 of the thermal clamps (thermal actuators for clamping the shuttle) is actuated. Thus the thermal actuator is engaged with the shuttle (figure 1). Next, the thermal actuator is actuated, and the shuttle is pulled one step forward. Pair #2 of the thermal clamps is then used to fix the shuttle in the current position. By appropriate sequencing the input voltages to the actuators, smooth motion of the shuttle can be achieved.

It is to be noted that the engaging folded beams (figure 1) are critical elements for the proper operation of this device, and they are designed to have high stiffness in the ***y*** direction, and low stiffness in the ***x*** direction, so that the normal force and friction between the grips and the shuttle is sufficiently high to avoid slippage, and at the same time small portion of the force generated by the thermal actuator (the rightmost thermal actuator in figure 1) is consumed by spring force in the engaging beams. One approach to increase the friction between the shuttle and the clamps is to use engaging teeth along the shuttle where it gets engaged with the folded beams. However, this is not implemented in this design, since it would limit the step size of the actuation to the distance between adjacent teeth, which is typically a few microns.

One main advantage of this type of thermal actuation over available thermal actuators is that, especially if used in air, because of the long distance between the actuators and the sample (more than 700 µm) and also high thermal resistance between the clamps and the shuttle (due to small contact area between the teeth of the engaging folded beams and the shuttle), most of the thermal energy is dissipated to the air and the substrate before reaching the sample. Therefore, no significant heating is expected to happen on the sample.

6. Design

The designs of the three parts of the tension test platform are discussed in this section: the actuators, loadcell and the imaging/mounting platform. The physical constants used in the analysis are shown in Table 1.

Table 1. Design parameters (polysilicon)

Parameter	**Value**
Young's modulus, E	155 GPa
Poison ratio, υ	0.23
Resistivity, ρ	0.001 Ω.cm
Polysilicon Thermal conductivity, k_p	30 $Wm^{-1}C^{-1}$
Specific heat, C_p	750 $JKg^{-1}C^{-1}$
Density, D	2330 Kg/m^3
Air Thermal conductivity, k_{air}	0.026 $Wm^{-1}C^{-1}$
Coefficient of thermal expansion α	$2.26x10^{-6}$

6.1 Thermal actuators

As discussed in section 5, five thermal actuators are considered for the smooth motion of the shuttle. The thermal actuators consist of V shaped beams arranged parallel to each other, and anchored on both sides (figure 3). A detailed description of these actuators and their operation principle can be found in [2]. In the current design, the bend angle of the beams was chosen to be 6°,

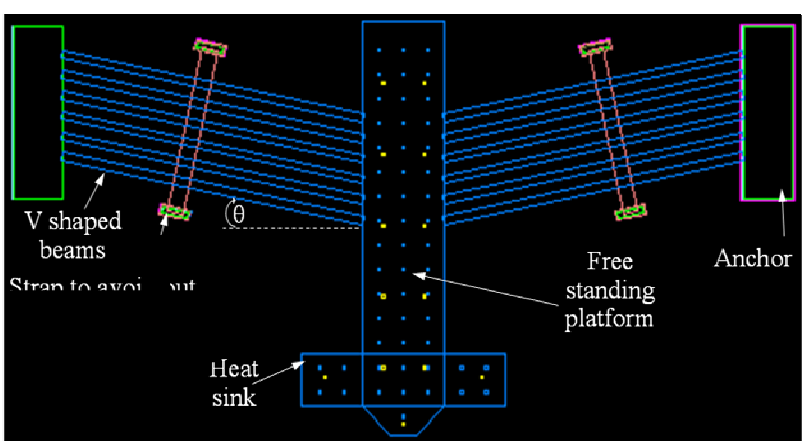

Figure 3. Cad drawing of the thermal actuator (layer P3 in SUMMIT V)

the beams were 350 μm long, 8 μm wide and 2.25 μm high. Passing ~10 mA current in the beams, they can provide a free motion of ~1.56 μm.

6.2 Analysis of the thermal actuators in the transient mode

A detailed analysis of the thermal actuators in the transient and steady state can be found in [2,5]. Based on these analyses, the approximate maximum temperature (T_{max}) and time constant (τ) of the heating/cooling rates can then be obtained as:

$$T_{\max} = \frac{V^2}{\rho} \frac{t_{air} h}{k_{air} S l^2} \tag{1}$$

where V is the actuation voltage and

$$\tau = \frac{C_p D h t_{air}}{k_{air} S} \tag{2}$$

For the current design, the value of the time constant equals 183 μs. The minimum period for actuation can be approximated to ~5τ, which is when the temperature solution of equation 1 is within 99% of the steady state solution (assuming an exponential raise and decay). This time is sufficient for the actuator to heat up during actuation to a temperature close enough to the steady state temperature, and cool down close enough to room temperature when actuation voltage is removed.
The displacement of the thermal actuator in each step as a function of temperature can be found as [2]:

$$\Delta = \alpha \Delta T \sin(\theta) l \Big/ \left[\sin^2(\theta) + \cos^2(\theta) \times \left(\frac{l}{w} \right)^2 \right] \tag{3}$$

In this equation, θ is the inclination angle of the beams (6°), and ΔT is the temperature change (=T_{max} in equation 1).

6.3 Analysis of the loadcell

The loadcell used in this design is a typical folded beam loadcell as shown in figure 1. This loadcell consists of two pairs of identical folded beams one inside the other, each with the spring constant of ~1 N/m. The stiffness of this loadcell can be calculated as:

$$K = 2 \times \frac{12EI}{l^3} \tag{4}$$

where I and l are the moment of inertia and length of the beam, respectively (beams are identical in this case).

6.4 Analysis of the imaging/mounting platform

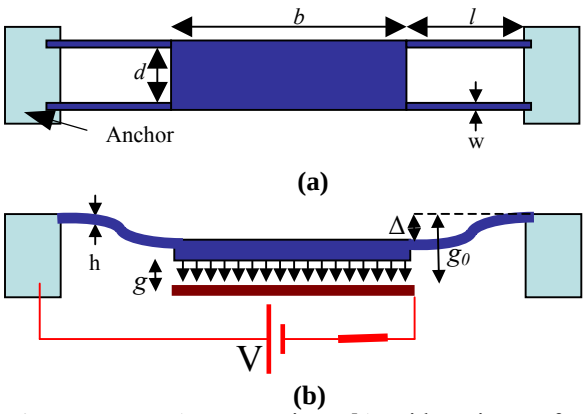

Figure 4. **a)** Top view **b)** side view of the imaging/mounting plate after actuation

The mounting/imaging platform consists of a flat polysilicon plate in P3 layer which is connected to two thin beams on each side. The other sides of the beams are anchored to the substrate. Before and after the tension test, samples rest on the plate, while during tension test, the plate is actuated electrostatically and pulled down, not to be in contact with the sample. A simplified model of the plate is presented here (figure 4). At equilibrium, the vertical spring force in each beam due to deformation Δ is balanced with the capacitive force between the plate and the substrate; therefore,

$$\frac{1}{2}\varepsilon_0 \frac{bd}{g^2} V^2 = 4Ew\left(\frac{h}{l}\right)^3 \Delta \qquad (5)$$

It is desired that at a voltage of 25 V or below, the deflection reaches a value of a few hundreds of nanometers (clearance between the sample and the plate). For this purpose, the length, and width of the beams are chosen to be 80 µm and 2 µm, respectively. The plate dimensions are 200 µm by 26 µm. The width of the plate is determined by the sample length which rests on the plate. In this case, the vertical motion of the plate at 25 V is found to be 0.198 µm.

7. Summary

The proposed MEMS testing platform is designed to study a wide range of mechanical behaviors. According to the preceding analysis, the maximum speed of the actuation mechanism is on the order of mm/s which for a common fiber gauge length (~30 µm) corresponds to ~10^2 s^{-1} strain rate. Slower strain rates can be achieved by tuning the input signals. The maximum displacement for the present actuation mechanism is ~ 100 µm, corresponding to ~300 % strain.

The force is measured by leaf spring loadcells with resolution of ~20 nN. The latter can be improved by a factor of 2 for softer samples. The maximum measurable force is limited by the strength of the loadcell beams. In the current design, this value is ~ 100 µN. The actuation mechanism employed allows for large displacements (as large as 100 µm) without affecting the maximum force capacity and the step size of the actuators. Therefore, constant deformation rates (and constant engineering strain rates) can be achieved over a wide range of displacements.

In order to facilitate sample manipulation on the device, a removable suspended platform is placed at the gauge section on which the sample rests during the sample mounting

process and during post tension test processing under SEM. Electrical actuation separates the sample from the plate for the tension test.

The aforementioned advantages of this design over other conventional MEMS devices make the current device a suitable platform to study mechanical behavior over a large range of deformations as well as superplasticity and time dependent mechanical behavior in nanostructures such as polymeric nanofibers.

References

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