

Design of a bent beam electrothermal actuator for *in situ* tensile testing of ceramic nanostructures

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Abstract

A necessary condition to include nanoscale materials in the design of high-performing as well as reliable electrical and electromechanical devices is the availability of a sufficiently deep knowledge of their mechanical behavior. Up to date, the most powerful tools for mechanical characterization of nanosamples are properly designed microelectromechanical systems (MEMS), due to their compatibility with scanning/transmission electron microscopy (SEM/TEM) and high resolution force/displacement measurements. Herein, we report about the design of a MEMS platform for *in situ* SEM tensile testing of nanoscale samples. This is characterized by a very compact structure, based only on a bent beam electrothermal actuator, which performs both actuating and sensing functions. The size of the structural components of the present device is chosen with the aim of testing ceramic nanowires, but the resulting configuration can be applied also for other material samples.

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1. Introduction

The outstanding properties reported for nanoscale materials, like nanosheets, nanowires and nanotubes, can be exploited in a new generation of high-performing electrical and electromechanical devices.^{1,2} In this context, an exemplary case is given by graphene, which presents excellent mechanical, electrical and optical properties (e.g., Young modulus and carrier mobility, to cite only a few).^{3,4} Furthermore, attention has also been devoted to different kinds of nanowires, like silicon nanowires, characterized by giant piezoresistance effects,⁵ as well as ceramic nanowires, like zinc oxide and gallium nitride nanowires,^{6,7} whose piezoelectric properties make them suitable for energy harvesting applications in self-powered nanodevices.

A key factor enabling for an accurate and reliable design with such new materials is the availability of sufficient information about their mechanical, as well as electromechanical, behavior.⁸

However, in spite of the intense work already done, many questions about the behavior of materials at the micro- and nanoscale remain still open. The scattering or lack of experimental data, as well as the need of validity assessment, testify that there is still room for further investigation.⁹ This is a challenging task, though.

In fact, the small size characterizing nanoscale structures compromises the effectiveness of manipulation and testing with traditional techniques. For this reason, during the years, suitable experimental protocols and testing systems have been developed. Among these, the most promising techniques are based on micro-electro-mechanical systems (MEMS) technology. The most important advantage they offer relies on the compatibility of MEMS devices with scanning/transmission electron microscope (SEM/TEM) chambers, which enable for real-time imaging of the sample deformation, while providing high displacement and force resolution.¹⁰

The literature offers different examples of MEMS-based tensile testing stages. Most of them share the same architecture, composed of an actuator (which applies force/displacement to a sample) and a sensor (for force/displacement measurement) with a small gap in between for sample positioning.^{11–13} Here, the actuator may be thermal¹¹ or electrostatic,¹³ and the

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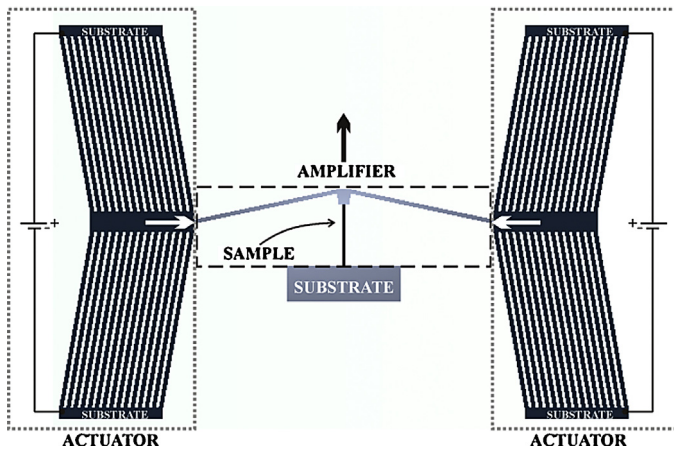


Fig. 1. Schematic of the proposed tensile testing stage, where the sample is connected to a bent beam motor at one end, and anchored to the substrate at the other end.

sensor may be mechanical^{12,13} or electrical.¹¹ In the first case, the sensor deformation during the test is acquired through SEM pictures, and then converted into force by multiplying it by the sensor spring constant¹³ whereas, in the second case, more sophisticated design and experimental setup are required in order to provide an electrical measurement of the sensor deformation (e.g., load).¹¹ In this kind of architecture, the sensor and the sample experience the same load. However, the literature offers other examples, where the tensile stage is arranged in order for the sensor and the sample to undergo instead the same displacement. Some examples can be found in,^{14,15} where the thermal/electrostatic actuator performs both actuating and sensing functions. Into another case,¹⁶ the displacement is applied through a nanoindenter which pushes against a MEMS platform, where a system of springs convert the incoming compressive action into a tensile force delivered to the sample.

The tensile stage presented in this paper has a quite simple structure, only comprising a bent beam motor. This has been classically used as actuator,¹⁷ but in the present device it serves also as load sensor. Details about its design will be diffusively discussed in the following sections. In particular, the size of its structural components is chosen with the aim of testing ceramic samples, like zinc oxide and gallium nitride nanowires. Nevertheless, the resulting configuration can be applied for other material samples.

2. Device presentation and design requirements

The proposed MEMS stage is basically composed of a bent beam motor, as depicted in Fig. 1. With respect to a previous proposed device¹⁸, in this case there is no need for any additional sensing structures, since the motor can be designed in order to perform both actuation and sensing functions, as will be explained in the following.

From a structural point of view, the device includes two thermal actuators (placed at the right and left sides in Fig. 1) provided with a classical v-shaped beams configuration. When a voltage is applied between their anchor points, current flows and generates

heat by Joule effect. Thus, the beams expand, moving horizontally along the direction indicated by the arrows in Fig. 1. Such displacement is delivered on each side of the central structure (e.g., referred to as amplifier in Fig. 1). This comprises a number of v-shaped beams, whose central part is connected to a shuttle, which is in turn connected to the sample to be tested (anchored to the substrate on the other side). The most interesting feature of the amplifier is concerned with its vertical displacement (which is also transferred to the sample) which results from the horizontal movements of the side actuators. In fact, upon proper design, the magnitude of such vertical displacement can be few times greater than the original horizontal displacement.

The novelty of the present configuration is, however, the sensing function, rather than displacement magnification, intended to be performed by the amplifier. This can be achieved by providing the amplifier with a stiffness comparable to that of the sample to be tested. In this way, the presence of the sample affects the vertical displacement achieved by the amplifier into a relatively significant amount. Thus, the difference between the displacement with and without a sample mounted can then be converted into force, by multiplying it by the amplifier stiffness. A similar idea was at the basis of the thermal actuator/sensor considered in.¹⁴ However, in that case there was a significant temperature gradient affecting the sample. In this case, as in Ref.¹⁸ the temperature increase due to the Joule effect is not a problem, since the actuators can operate at low voltage (e.g., low temperature), thus generating a small displacement, because this is then amplified by the central structure.

The performance the device has to achieve depends on the material sample to be tested. Because of the increasing attention gained by ceramic nanowires, the present design is customized with reference to exemplary zinc oxide/gallium nitride nanowires. In particular, considering nanowires with 4 μm length and diameters up to 100 nm, and given their mechanical properties,^{19–21} the device should be able to generate up to 1 μm displacements and force up to 100–200 μN. However, the device is versatile and other nanostructures than these could be tested, too.

The following sections provide more details about the design methodologies of the thermal actuators and mechanical amplifier, including both analytical and multiphysics numerical modeling.

3. Design of the thermal actuators

The thermal actuators have a classical configuration with a freestanding shuttle, anchored to the substrate through a series of v-shaped beams. When a voltage is applied across the v-shaped beams, the corresponding current flow generates heat by Joule effect. The dissipated heat causes thermal expansion of the beams, which results into a horizontal movement (Fig. 2a).

According to a detailed analysis reported in Ref. ²² the actuator axial stiffness and displacement can be expressed as:

$$u = \alpha \Delta T \frac{\sin \theta}{\sin^2 \theta + (b/L)^2 \cos^2 \theta} \quad (1)$$

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