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Piezoresistive InGaAs/GaAs Nanosprings with Metal Connectors

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ABSTRACT

This paper presents the fabrication, assembly, and characterization of piezoresistive nanosprings for creating nanoelectromechanical systems. The fabrication process is based on conventional microfabrication techniques to create a planar pattern in a 27nm thick, n-type InGaAs/GaAs bilayer that self-forms into three-dimensional structures during a wet etch release. As the nanosprings have lower doped thin and flexible layers, small metal pads have been attached to both sides for achieving stable ohmic contact with electrodes. Nanorobotic manipulation is applied to assemble the nanosprings between electrodes using electron-beam-induced deposition inside a scanning electron microscope, and the bridged nanosprings were then characterized for electromechanical properties. With their strong piezoresistive response, low stiffness, large-displacement capability, and excellent fatigue resistance, they are well-suited to function as sensing elements in high-resolution, large-range electromechanical sensors.

Many three-dimensional (3-D) helical structures with micro- and nanofeatures have been synthesized from different materials. Typical examples include microcoils based on amorphous carbon,1 nanocoils based on carbon nanotubes,2 and zinc oxide helical nanobelts.3,4 Because of their interesting morphology, as well as mechanical,5 electrical,6 and electromagnetic properties, these micro/nanostructures can be used as components for micro- and nanoelectromechanical systems (MEMS and NEMS) such as springs, inductors, sensors, and actuators.

A new method of creating structures with nanometer-scale dimensions has recently been presented.7 The structures are created through a top-down fabrication process in which a strained nanometer thick heteroepitaxial bilayer curls up to form 3-D structures with nanoscale features. Several techniques have been proposed to improve the controllability over the fabrication process in terms of the resulting length, shape, and orientation of structures based on III−V compounds.8−12 Recently, the electrical and mechanical properties of SiGe/Si/Cr and SiGe/Si nanosprings were characterized separately through experiments and simulation.13 The fabrication and mechanical characterization of InGaAs/GaAs nanosprings has also been described.14 ZnO nanobelies were also characterized in their mechanics of superelasticity and nanofracture.15 More characterizations of nanostructures were also studied using in situ microscopy methods.16,17

However, to achieve stable electromechanical characteristics such as piezoresistivity, it is required to assemble the nanosprings between electrodes by soldering them with high precision. Attaching metal electrodes to these nanostructures are useful for the assembly and the achievement of an Ohmic electrical contact. Magnetic field assisted assembly of carbon nanotubes with ferromagnetic metal (Ni) ends proved to be useful for both electrical property characterization and device assembly.18,19 Dexterous robotic manipulation with multiple end effectors can be more useful for the stable dynamic property characterization.20

Nanosprings can serve as a mechanism to transduce force to displacement. The deformation is detected through piezoresistance. This sensing mechanism was demonstrated previously with other structures on the micro- and nanoscale. For example, piezoresistive microcantilevers have been used to characterize low-force electrical contacts.21 Moreover, an
The results have previously been validated with experimental results for similar structures. Linear simulation was carried out, so that the results are valid for small displacements only.

Table 1. Specifications of Nanosprings Used in Experiments and Simulations

<table>
<thead>
<tr>
<th>nanospring 1</th>
<th>nanospring 2</th>
<th>nanospring 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness InGaAs</td>
<td>11.6 nm</td>
<td>15.6 nm</td>
</tr>
<tr>
<td>thickness GaAs</td>
<td>15.6 nm</td>
<td>10 nm</td>
</tr>
<tr>
<td>thickness Au</td>
<td>5.5 nm</td>
<td>6.6 µm</td>
</tr>
<tr>
<td>diameter of nanospring</td>
<td>2.1 µm</td>
<td>3.0 µm</td>
</tr>
<tr>
<td>InGaAs/GaAs doping (N_D)</td>
<td>6 × 10^{18} to 1 × 10^{19} cm^{-3}</td>
<td>N_D1 &lt; N_D2 &lt; N_D3</td>
</tr>
<tr>
<td>pitch</td>
<td>5.5 µm</td>
<td>6.6 µm</td>
</tr>
<tr>
<td>stripe width</td>
<td>5.5 µm</td>
<td>6.6 µm</td>
</tr>
<tr>
<td>number of turns</td>
<td>6</td>
<td>5.5</td>
</tr>
<tr>
<td>stiffness (simulation)</td>
<td>0.020 N/m</td>
<td>0.024 N/m</td>
</tr>
<tr>
<td>torsion coefficient: T_s</td>
<td>0.118</td>
<td>0.15</td>
</tr>
</tbody>
</table>

increased piezoresistivity could be demonstrated for Si nanostructures.22,23

In this paper, InGaAs/GaAs nanosprings were fabricated with one end fixed to nonscrolling supports for control over their position. Moreover, we present an extension to the fabrication process described in ref 14. We demonstrate the fabrication of nanosprings with small metal pads attached on both ends. These pads help to achieve good electrical contact, which is required for electromechanical characterization, but can also be useful for the assembly of more complex devices with the self-sensing nanosprings as components. The electromechanical response of the piezoresistive nanosprings is characterized using nanomanipulation in scanning electron microscopy (SEM). Their stiffness and stress distribution of each bilayer are simulated using the model that was validated for similar structures in ref 14. Moreover, the fatigue behavior of the structures is investigated during oscillation at resonant frequency.

Figure 1 illustrates the fabrication process. The initial layers were grown on semi-insulating GaAs (Freiberger Compound Materials) using a molecular beam epitaxy system (VEECO, Gen III MBE) equipped with a valved crackler for As and solid sources for Ga and In (Figure 1a). For n-type doping, a solid Si source was used. Substrate temperature was determined by diffuse reflectance spectroscopy. After a thin GaAs buffer layer, the 500 nm thick sacrificial AlGaAs layer is deposited. The layer contains 20% Ga in order to prevent oxidation. 

The sacrificial layer in previous designs was made of AlAs. The oxidation of these layers after exposure damaged the InGaAs/GaAs bilayer. On top of the sacrificial layer the InGaAs/GaAs layer is deposited which later self-forms into the nanosprings. An In content of 15% in the InGaAs layer was determined by X-ray diffraction (XRD) measurements. The thickness of this layer must be smaller than the critical thickness to maintain elastic strain.24,25 The layer properties along with other specifications of the structures are summarized in Table 1.

To observe the effect of different doping concentrations of InGaAs/GaAs to the piezoresistive response, two wafers with different doping concentrations were used for the experiments.

During the deposition of the InGaAs/GaAs bilayer on this wafer, it was attempted to get a slightly lower doping concentration than on the wafer that was used for nanosprings 2 and 3 (Table 1). From the results it seems that the doping concentration was too high which resulted in a partial self-compensation and, therefore, in a decrease in the effective doping concentration. The doping concentration of the three structures is not exactly known but is specified in Table 1 with the high 10^{18} cm^{-3} range.

The initial pattern can be created through photolithography. S1805 was used as a resist (Figure 1b). After the development of the resist with MF319, reactive ion etching (RIE) with a mixture of 95 sccm H_2 and 5 sccm CH_4 gases at a pressure of 130 µbar, a substrate temperature of 10 °C, and a power of 130 W was used to transfer the pattern to the InGaAs/GaAs bilayers at an etch rate of approximately 3.3 nm/s (Figure 1c). Next, the Cr/Au pads on the ends of the nanosprings, and the bars to which the structures are fixed at the end were created through a lift-off process with negative photoresist ma-N1410 and ma-D376XP as a developer (Figure 1d). This developer is based on metasilicate and does not etch the underlying InGaAs/GaAs bilayer.

The Cr layer is 10 nm thick and serves as an adhesion layer. The 100 nm thick Au layer is used for electrical contacts (Figure 1e,f). Finally, a 2% HF aqueous solution was used to selectively etch the AlGaAs sacrificial layer under the InGaAs/GaAs heterostructures for the self-forming of the nanostructures (Figure 1g). During this wet etch, the patterned bilayer curled up along a (100) direction releasing the internal strain and forming 3-D structures. The direction of the scrolling is determined by the anisotropy in stiffness of the InGaAs/GaAs bilayer. After the wet etch release, the chips were rinsed in deionized water and subsequently in isopropyl alcohol. Next, they were dried with a supercritical CO_2 dryer so that the structures would not be damaged from surface tension. After exposure to air at room temperature a thin native oxide layer forms on the surface of the released structures.26
The dimensions of the nanosprings used in the simulation were the same as in the experiments, as summarized in Table 1. They were modeled using two different layers, similar to the actual nanosprings (Figure 5a). Values of the materials properties in the model were taken from ref 27 with the rule of mixture applied for the InGaAs layer. Boundary conditions

Figure 2. Nanosprings with two metal pads during manipulation: (a) picking up; (b) during measurement with zero deformation; (c) during measurement with maximum deformation; (d) after the structure breaks with too much force.

Figure 3. $I$–$V$ curves for different deformations of the nanosprings listed in Table 1: (a) nanospring 1; (b) nanospring 2; (c) nanospring 3; (d) the relation between bilayer stress and resistance.
were applied to both ends of the nanosprings. On both ends they were constrained from rotation around all three axes. Moreover, on one end they were constrained from all translational movements, and on the other end they were constrained from translational movement perpendicular to the axial direction. On this end, a force in the axial direction was applied so that the displacement of this end could be computed.

For the electromechanical characterization experiments, two nanomanipulators (Kleindiek, MM3A), each with two metal probes (Picoprobe, T-4-10-1 mm) with a tip radius of 100 nm attached, were installed inside an SEM (Zeiss, DSM 962).

The experimental procedure is illustrated in Figure 2. A nanospring was picked up by two probes to measure the

Table 2. Experimentally Obtained Quantitative Parameters in Full Range: Resistance (MΩ), Gauge Factor, and Piezoresistance Coefficient (10⁻⁸ Pa⁻¹)

<table>
<thead>
<tr>
<th></th>
<th>nanospring 1</th>
<th>nanospring 2</th>
<th>nanospring 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>resistance (MΩ)</td>
<td>394–568</td>
<td>42–102</td>
<td>84–158</td>
</tr>
<tr>
<td>gauge factor β(ε)</td>
<td>1.1</td>
<td>4.3</td>
<td>3.3</td>
</tr>
<tr>
<td>piezoresistance coeff.</td>
<td>−35.6</td>
<td>−24.5</td>
<td>−9.6</td>
</tr>
</tbody>
</table>

Table 3. Comparisons of Longitudinal Piezoresistance Coefficients (10⁻⁸ Pa⁻¹)

<table>
<thead>
<tr>
<th></th>
<th>bulk silicon</th>
<th>boron silicon</th>
<th>carbon silicon</th>
<th>nanotube silicon</th>
<th>nanowire silicon</th>
<th>nanospring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(10⁻¹⁰ Pa⁻¹)</td>
<td>1.7–9.4</td>
<td>4</td>
<td>∼400</td>
<td>3.5–355</td>
<td>996–3560</td>
</tr>
</tbody>
</table>

Figure 4. Plots showing the length of the nanosprings and the current at 1 V for different measurements: (a) nanospring 1; (b) nanospring 2; (c) nanospring 3.

Figure 5. Structural simulation for nanospring 1: (a) element closeups showing both layers; (b) bilayer stress distribution in GPa for axial tensile force of 500 nN on one end and fixed on the other end.

Figure 6. Electromechanical measurements: current at 1 V of a nanospring 3 corresponds with the applied force at each point.
resistance in large displacement range without substrate interference. One manipulator was used to break and pick up a nanospring on one side. For this purpose the nanosprings were fabricated with a small length between the support and the first metal pad. The other manipulator was used to make contact to the other side. In order to achieve good electrical contacts on both sides of the nanosprings, an electron-beam-induced deposition (EBID) with W(Co)$_6$ precursor was used. This way a voltage could be applied on both sides of the nanosprings and the current could be measured with a low-current electrometer (Keithley 6517A).

For the nanospring piezoresistivity measurement, we used fresh metal probe and EBID as shown in Figure 2. After a nanospring was attached as described above, a tensile force was applied to it by moving one probe away from the other in the axial direction (Figure 2b–d). Continuous frames of images were taken to detect the deformation, and I–V curves were recorded for the different positions. The characterization was carried out for three different nanosprings. Their dimensions are summarized in Table 1. It was checked from the images that the boundary conditions did not change significantly during the experiments. In Figure 2d, it can be seen that even after the nanospring broke the attachment to the probe did not change.

The SEM images were analyzed to extract the nanospring deformation for a certain I–V measurement. From these data, different plots can be generated. In Figure 3 different I–V curves are shown for different elongations. The current increases for an increasing axial elongation. After the self-scrolling of the structures, the outer InGaAs layer is under compressive stress while the inner GaAs layer is under tensile stress. Moreover, across the thickness of each layer the stress is inhomogeneous. When a tensile force is applied to the structure, the compressive stress in the InGaAs layer decreases and the tensile stress in the GaAs layer increases.

There is also shear stress, all of which make it difficult to model the exact stress state of these structures under a tensile load. Moreover, the piezoresistive response due to changes in this stress state is even more complex. For GaAs there are four physical mechanisms that cause changes in electrical resistance due to stress. First, the electron effective mass changes under stress leading to a change in mobility. Second, changes in stress cause the transfer of electrons between the high-mobility band gap minimum and low-mobility minima due to change of their relative energy. Third, stress can cause electrons to freeze to deep-level impurities. Fourthly, piezoelectric charges induced by stress gradients also change the resistivity. Besides these mechanisms for the piezoresistive behavior of the InGaAs/GaAs nanosprings, size effects influence the magnitude of the piezoresistive response, as has been reported previously for other types of nanostructures. For all of these reasons, the complete modeling of the changing stress state and piezoresistive response of the nanosprings in this work is very complex and has not been attempted yet.

To estimate the relation between the resistance change of nanosprings and the strain change, the InGaAs/GaAs bilayer resistance of extended nanospring before scrolling was...
measured. Intrinsic bilayer resistance was measured by probing the less underetched bilayer before it scrolls to nanospring. The measured \( I-V \) curve reveals that the resistance of extended nanospring before scrolling measures much higher than the one of the scrolled nanosprings. It shows the intrinsic beam type InGaAs/GaAs bilayer resistance with zero torsion before scrolling is much higher than the total resistance measurement of nanospring. In this case the probes are firmly applying enough pressure to make Ohmic contacts. Therefore the contact resistance of a nanospring does not take a big role in the total measured resistance of nanospring piezoresistivity at least in zero deformation.

The possible mechanism explanations are given. Panels a–c of Figure 3 show a series of consecutively recorded \( I-V \) curves along with axial deflections of each nanospring. Resistance of each nanospring decreases when nanosprings are elongated. The possible mechanisms of the resistance decrease of both the initial scroll process and the elongation of the scrolled nanospring can be explained by Figure 3d. During the scrolling process, the tensile stress \( X_1 \) of the InGaAs layer decreases much to the negative value (compressive stress) while the compressive stress \( X_2 \) of GaAs increases to the positive one (tensile stress). This results in the resistance decrease. When the scrolled nanospring is elongated, both layers undergo the same change of stress as was shown in Figure 3d which results in the resistance decrease as well.

We emphasize it is crucial to make a good physical contact between an electrode and a nanospring during electrical probing. In this study, when a tungsten probe mechanically contacted a nanospring, a moderate current of several dozen nanoamperes given 1 V voltage input was applied to pass through the electrode—nanospring circuit. For the measurement of nanospring’s piezoresistivity, strong electromechanical contacts should be made. EBID was applied to make interconnection soldering between two probes and a nanospring. We can clearly define a good enough contact for the piezoresistivity measurements based on the following several decision rules.

To evaluate the possible influence of the physical contact, proper contacts have been achieved based on the following steps before the piezoresistivity measurements. First, a stable contact can be recognized when the \( I-V \) curve on their sweeping steps is smooth and should show the typical behavior of semiconductors. It can be easily tested by measuring the \( I-V \) curve when the nanospring between two probes undergoes zero deformation. Because of a high resistance of the contact points, a locally generated high temperature caused the metal probe to be welded to the metal pads of the nanosprings forming a perfect physical contact between the two. This is one of the reasons why metal pads were attached to the nanospring, giving wider contact area. Wide contact area with well-made contacts was inevitable to constrain the boundary conditions of contacts and eventually useful for the full range piezoresistivity experiments shown in this paper. Panels a and b of Figure 2 show the most effective method to improve the intimacy of a physical contact. Second, a resistance change during the deflection of nanospring should be measured. Unstable contact gives an overall resistance increase when the nanospring is elongated in a very small deflection. It is mainly because the contact is becoming weaker by the elongation force. In the case where a compressive force is applied, contact resistance will be reduced which reduces the overall resistance measurement. Therefore, we confirm that contacts that are not made well enough have a positive resistivity relation with the strain by increasing the contact resistance when the nanospring between two probes is elongated. Third, a strong and firm contact was assured to know the behavior of intrinsic resistance change of nanosprings. We applied an EBID for much a longer time so the decrease of overall resistance during EBID is saturated. We can then be sure that there is no more improvement of contact. Therefore, we can measure intrinsic property of nanospring’s piezoresistivity. When such a firm contact is assured, overall resistance during elongation is decreased. Therefore, we find that the nanospring undergoes a negative piezoresistivity relation with the strain.

From Figure 3 it can be seen that both the resistance and the piezoresistive response are different for the three nanosprings in Table 1. The resistance range and the gauge factor of nanosprings are summarized in Table 2. The piezoresistive gauge factor \( \beta_{p,i}(\varepsilon) \) of the nanosprings is given by

\[
\beta_{p,i}(\varepsilon) = (\Delta R(\varepsilon)/R_0)\varepsilon^{-1}
\]

where \( \Delta R(\varepsilon) \) is the resistance change, \( R_0 \) is the initial resistance at zero strain, and \( \varepsilon^{-1} \) is the strain. To compare the response of the measured nanospring piezoresistivity, the resistance range and the gauge factors were shown in Table 2. Nanospring 1 has a much higher resistance at zero elongation as well as a lower piezoresistive response. The chip that was used to fabricate this nanospring was taken from a different wafer. Besides its higher resistance, the nanospring with lower doping concentration also exhibits a lower piezoresistive response. Nanosprings 2 and 3 were made from the same wafer. The difference in resistance between these two structures can be due to the difference in contact resistance between the probes and the nanosprings.

Since each cycle of the piezoresistivity curve in Figure 4 was almost linear to the maximum elongations, we could evaluate the sensitivity of the nanospring’s piezoresistivity by the piezoresistance coefficients for the comparison with other nanostructures. The axial (longitudinal) piezoresistance coefficients \( \pi_i^p \) of three nanosprings were calculated from the measured \( I-V \) characteristics. \( \pi_i^p \) is defined as the relative change in conductivity per unit stress

\[
\pi_i^p = \frac{\Delta \sigma}{X \sigma_0}
\]

where \( \sigma_0 \) is the conductivity under zero stress and \( X \) is the stress. The piezoresistance coefficient was defined with resistivity \( \rho \) as \( \pi_i^\rho = \Delta \rho/X \rho_0 \). The conversion is \( \pi_i^\rho = -\pi_i^p \) for small \( \sigma \). Uniaxial stresses were applied on nanospring along their lengths by the method shown in Figure 2. Since the linearity of each cycle in Figure 4 is almost constant, the widest measured region of the cycles was chosen to
calculate the piezoresistance coefficients. Geometry information from the Table 1 was used as the parameters.

Table 2 summarizes the obtained results of three different nanosprings and mechanical parameters such as pitch and stiffness to see the relation between them. Doping concentrations on each nanospring were not considered because they were not exactly specified for each nanospring. Therefore the effect from the geometry is only considered as the effective parameters for simplification of the discussion. Torsion stress during axial elongation was assumed to be the most prevailing effect to the piezoresistivity of nanosprings. Mechanical stiffness of axial direction of helical nanostructures is known to be dominated by the torsion stress compared to the shear, bending, or tension.\textsuperscript{31} Since the torsion effect is inversely proportional to the pitch and the stiffness, pitch $\times$ stiffness was defined as the torsion coefficient ($T_c$) in this case for the comparison (Table 1). The $T_c$ of nanospring 2 is 1.271 times higher than that of nanospring 1. And the $T_c$ of nanospring 3 was 1.805 times higher than that of nanospring 1. The piezoresistance coefficient is increased when the $T_c^2$ is decreased with inversely proportional relation between them. Their products of the two coefficients for three nanosprings remain close to the mean value of $-4.94\times10^{-8}$ but with standard deviation of $0.58\times10^{-8}$. It can be explained by the fact that nanosprings used for these experiments have different doping concentrations.

These obtained piezoresistance coefficients of nanosprings were compared with other elements as the piezoresistors. All reported piezoresistance coefficients of bulk silicon, boron-doped silicon, carbon nanotube, and silicon nanowire are summarized in Table 3.\textsuperscript{22,32–34} Especially silicon nanowires were recently reported as the unusually high piezoresistance effect from the size effect in ref 22. The piezoresistance coefficients of the nanosprings are even much higher than those of silicon nanowires. These results can be explained by the benefit of nanospring’s flexibility considering the eq 2 since the tiny input stress ($X$) can cause the resistivity change ($\Delta\rho/\rho_0$). At least the torsion stress effect is considered to affect much to the high piezoresistive response of the nanosprings. The unusually high piezoresistive nanosprings are the promising nanostructures to be used as the elements of ultra-high-resolution electromechanical devices such as force sensors.

The piezoresistance of the structures can further be increased if Al is incorporated in the bilayer.\textsuperscript{30} Increasing the Al content, however, reduces the etch selectivity with the Al$_0.8$Ga$_{0.2}$As sacrificial layer.\textsuperscript{35}

In Figure 4 the change in resistance is plotted versus the change in length for all nanosprings. All three results have one trend in common: During the repeated cycles of pulling and pushing the resistance at zero deformation increases. There are two ways to explain this. The most probable reason is that under repeated loading and unloading the contact resistance increased because the attachment between the probes and the nanospring changed. From the transmission line model (TLM), the resistance at zero deformation depicts the contact resistance if we assume the initial contact resistance as static zero.\textsuperscript{36} The linearity of resistance versus deflection at each cycle proves that contact resistance at each deflection was maintained as static. Another reason can be that charging and joule heating in the SEM caused an increase in the resistance of the nanosprings.

As the initial contact was made by EBID, nanosprings have initial high temperature but cool down during the measurement. To prove the e-beam effect inside SEM, another experiment was performed. We made the same configuration of a nanospring between two probes and measured the resistance change. The resistance was measured at the same interval of piezoresistivity measurement. Nanosprings show the temperature dependence. However, the increase of the average resistance is not caused by some intrinsic property of the nanosprings but by the entire measurement system. For nanosprings that are integrated with stable electrical connections into some system outside SEM, a repeatable output can be expected. From the results in Figure 4 it can also be seen that the response is almost linear at most points. For the stable electromechanical sensor applications, the dynamic contact resistance analysis is important as we can easily calibrate the initial contact resistance as long as it is static.

Finite element simulation was used to estimate the stiffness of the nanosprings and the bilayer stress distribution (Table 1). In Figure 5, a plot of the displacement along the axial direction is shown for nanospring 1 from Table 1 with an applied axial force of 0.1 $\mu$N. The displacement of the end where the axial force is applied is 5 $\mu$m. Therefore the axial stiffness of the structure is 0.02 N/m. In Figure 5a, the closeups show both layers in the model which includes an inner layer (GaAs) and an outer layer (InGaAs). To show the bilayer stress distribution when a tensile force is applied to the structure, a stress state simulation was conducted. A stress state distribution in each layer when a tensile force of 500 nN is applied to the structure is shown in Figure 5b. An initial stress of the structure in zero strain was assumed to be zero. The tensile stress $X_2$ of the inner GaAs layer was increased to 0.802 GPa while the compressive stress $X_1$ of the outer InGaAs layer decreases to $-0.743$ GPa. This stress mismatch can be the possible mechanism to cause the resistance change of nanosprings.

Force calibration of the single nanospring in axial direction using an as-calibrated atomic force microscope cantilever can be referred from the previous work of ref 14. On the basis of the stiffness estimation, force versus current curve of nanospring 3 is shown in Figure 6. The current at 1 V corresponds with the applied force at each point for 4.5 times of repeated compressive and tensile cycle loadings.

In order to show that the nanosprings can operate as sensor elements over a long time, another experiment was carried out. A nanospring without metal pads was picked up with one probe while another probe was moved close to the free-standing end. When a sinusoidal voltage with an amplitude of 5 V was applied between the two probes, the nanospring started to oscillate due to the electrostatic force between the nanospring and the other probe. Depending on the position of the second probe relative to the nanospring axis, different modes of oscillation could be induced. A nanospring was
excited at its resonance frequency both in bending mode (4.9 kHz) and in the axial displacement mode (10.5 kHz). Since the resonance frequency did not change during more than 10⁶ cycles in both modes, it can be assumed that the mechanical properties of the bilayer material do not change with multiple loading. Images from these experiments are shown in Figure 7.

Nanospring structures with metal pads attached on both sides were fabricated using conventional microfabrication techniques. With the metal pads, good electrical contact can be achieved. Besides the electromechanical characterization, such connectors also allow for the integration of these structures into more complex assemblies. Nanomanipulation structures at their resonance frequency and investigate their mechanical properties of the bilayer material do not change with multiple loading. Images from these experiments are shown in Figure 7.

Supporting Information Available: Figure showing a fully extended nanospring, a scrolled nanospring, resistance measurement of extended nanospring before scrolling, and its I–V curve. This material is available free of charge via the Internet at http://pubs.acs.org.

References