Hybrid Nanorobotic Approaches to NEMS

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Abstract

Robotic manipulation at the nanometer scale is a promising technology for structuring, characterizing and assembling nano building blocks into nanoelectromechanical systems (NEMS). Combined with recently developed nanofabrication processes, a hybrid approach to building NEMS from individual carbon nanotubes (CNTs) and SiGe/Si nanocoils is described. Nanosensors and nanoactuators are investigated from experimental, theoretical, and design perspectives.

Key words: nanorobotics, nanoassembly, nanomanipulation, NEMS, carbon nanotubes, nanocoils

I. Introduction

Despite the claims of many "futurists," the form nanorobots of the future will take and what tasks they will actually perform remain unclear. However, it is clear that nanotechnology is progressing towards the construction of intelligent sensors, actuators, and systems that are smaller than 100nm. These nanoelectromechanical systems (NEMS) will serve as both the tools to be used for fabricating future nanorobots as well as the components from which these nanorobots may be developed. Shrinking device size to these dimensions presents many fascinating opportunities such as manipulating nanoobjects with nanotools, measuring mass in femto-gram ranges, sensing forces at pico-Newton scales, and inducing GHz motion, among other new possibilities waiting to be discovered. These capabilities will, of course, drive the tasks that future nanorobots constructed by and with NEMS will perform.

The design and fabrication of NEMS is an emerging area being pursued by an increasing number of researchers. Just as with MEMS, NEMS design is inextricably linked to available fabrication techniques. However, though the development of microfabrication processes has become somewhat stable over the past decade, nanofabrication processes are still being actively pursued, and the design constraints generated by these processes are relatively unexplored. Two approaches to nanofabrication, top-down and bottom-up, have been identified by the nanotechnology research community, and the topic of this paper is how these trends can be integrated through robotics resulting in new classes of NEMS devices.

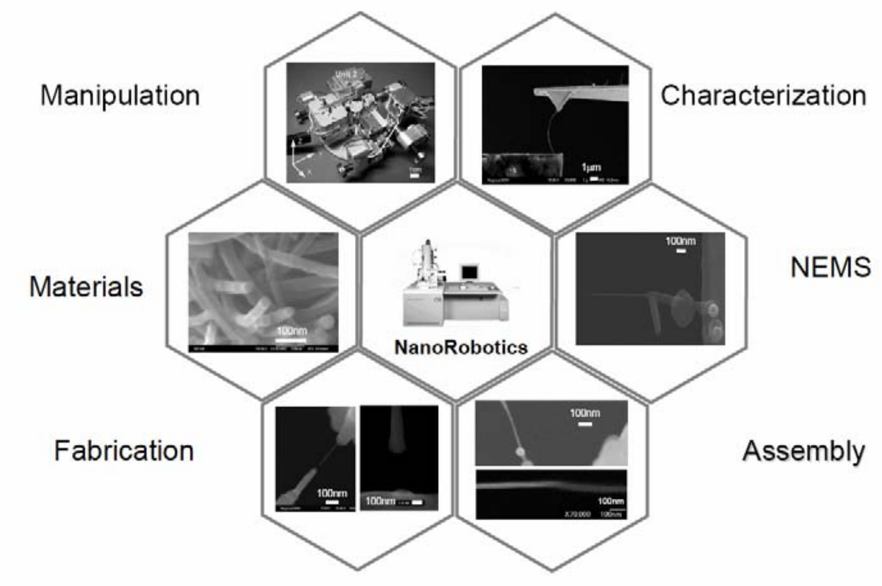


Fig. 1. A nanorobotic manipulation approach to NEMS.

Top-down and bottom-up nanofabrication strategies are being independently investigated by various researchers. Top-down approaches are based on microfabrication and include technologies such as nano-lithography, nano-imprinting, and chemical etching. Presently, these are 2D fabrication processes with relatively low resolution. Bottom-up strategies are assembly-based techniques. Currently these strategies include techniques such as self-assembly, dip-pen lithography, and directed self-assembly. These techniques can generate regular nano patterns at large scales. With the ability to position and orient nanometer scale objects, nanorobotic manipulation is an enabling technology for structuring, characterizing and assembling many types of nanosystems (shown in Fig. 1) [1]. By combining top-down (Fig. 2(a)) and bottom-up processes (Fig. 2(b)), a hybrid nanorobotic approach (Fig. 2(c)) based on nanorobotic manipulation provides a third way to fabricate NEMS by structuring as-grown nanomaterials or nanostructures. In this system, nanofabrication based top-down processes and nanoassembly based bottom-up processes can be performed in an arbitrary order. Consider nanofabrication processes in which nanomaterials or nanostructures can be fabricated into nano building blocks by removing unwanted parts. These building blocks can then be assembled into NEMS. Conversely, nanoassembly can be performed first and nanomaterials or nanostructures can be assembled into higher-level (i.e. more complex, 3D, arrays, etc.) structures, and then the high-level structures can be further modified into NEMS by nanofabrication.

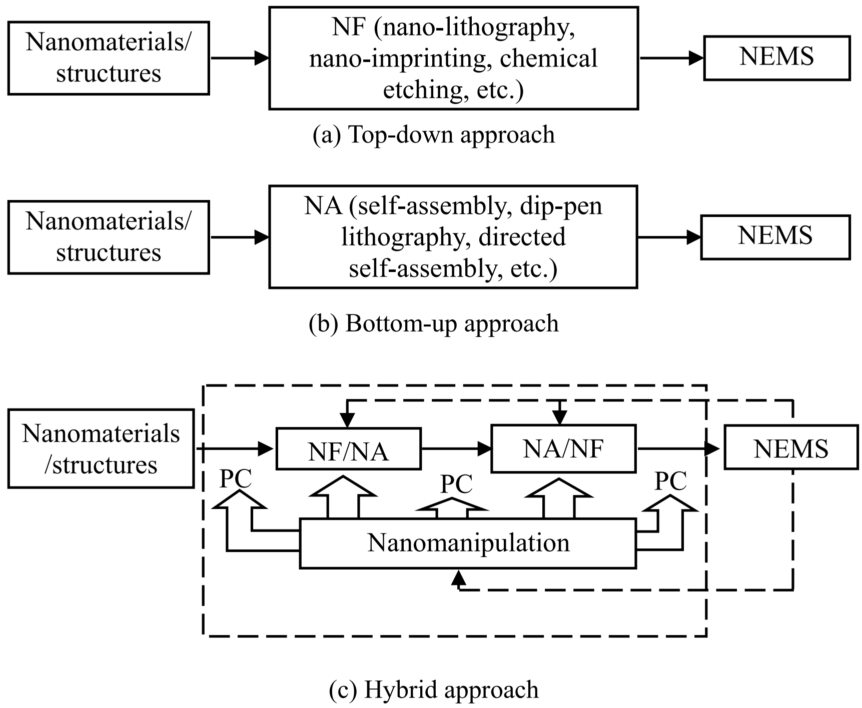


Fig. 2. Approaches to NEMS (PC: Property Characterization, NF: Nano Fabrication, NA: Nano Assembly)

Nanorobotic manipulation enables this hybrid approach for creating NEMS that can attain a higher functionality because they possess more complex structures. Moreover, property characterization can be performed after intermediate processes, and *in situ* active characterization can be performed using manipulation rather than conventional static observations. The impact of the hybrid approach on robotics is twofold: it expands the lower limit of robotic exploration further into the nanometer scale, and it will provide nanoscale sensors and actuators and assembly technology for building nanorobots. Nanomaterial science, bionanotechnology, and nanoelectronics will also benefit from advances in this new nanomanufacturing technique from the perspectives of property characterization, fabrication and assembly.

This paper introduces carbon nanotubes (CNTs) and nanocoils in Section II. In Sections III and IV, the assembly of individual nanotubes and nanocoils into NEMS are presented along with characterization results.

II. Carbon Nanotubes and Nanocoils for NEMS

Carbon nanotubes [2] and nanocoils have been used as base materials and structures because of their exceptional properties and unique structures. For NEMS, some of the most important characteristics of nanotubes include their nanometer diameter, large aspect ratio (10-1000), TPa scale Young's modulus, excellent elasticity, ultra-small interlayer friction, sensitivity of conductance to various physical or chemical changes, and charge-induced bond-length change. Helical 3-D nanostructures, or nanocoils, have been synthesized from different materials including helical carbon nanotubes [3] and zinc oxide nanobelts [4]. A new method of creating structures with nanometer-scale dimensions has recently been presented [5] and can be fabricated in a controllable way [6]. 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. Helical geometries and tubes with diameters between 10nm and 10μm have been achieved. Because of their interesting morphology, mechanical, electrical, and electromagnetic properties, potential applications of these nanostructures in NEMS include nanosprings [7], electromechanical sensors [8], magnetic field detectors, chemical or biological sensors, generators of magnetic beams, inductors, actuators, and high-performance electromagnetic wave absorbers. NEMS based on individual single- or multiwalled carbon nanotubes (SWNTs, MWNTs) and nanocoils are of increasing interest, indicating that capabilities for incorporating these individual building blocks at specific locations on a device must be developed.

Random spreading [9], direct growth [10], self-assembly [11], dielectrophoretic assembly [12] and nanomanipulation [13] have been demonstrated for positioning as-grown nanotubes on electrodes for the construction of these devices. However, for nanotube-based structures, nanorobotic assembly is still the only technique capable of *in situ* structuring, characterization and assembly. Because the as-fabricated nanocoils are not free-standing from their substrate, nanorobotic assembly is virtually the only way to incorporate them into devices at present.

III. Individual Nanotube Based NEMS

Basic techniques for the nanorobotic manipulation of carbon nanotubes are shown in Fig. 3 [1]. These serve as the basis for handling, structuring, characterizing and assembling NEMS. Configurations of nanotools, sensors, and actuators based on individual nanotubes that have been experimentally demonstrated are summarized as shown in Fig. 4.

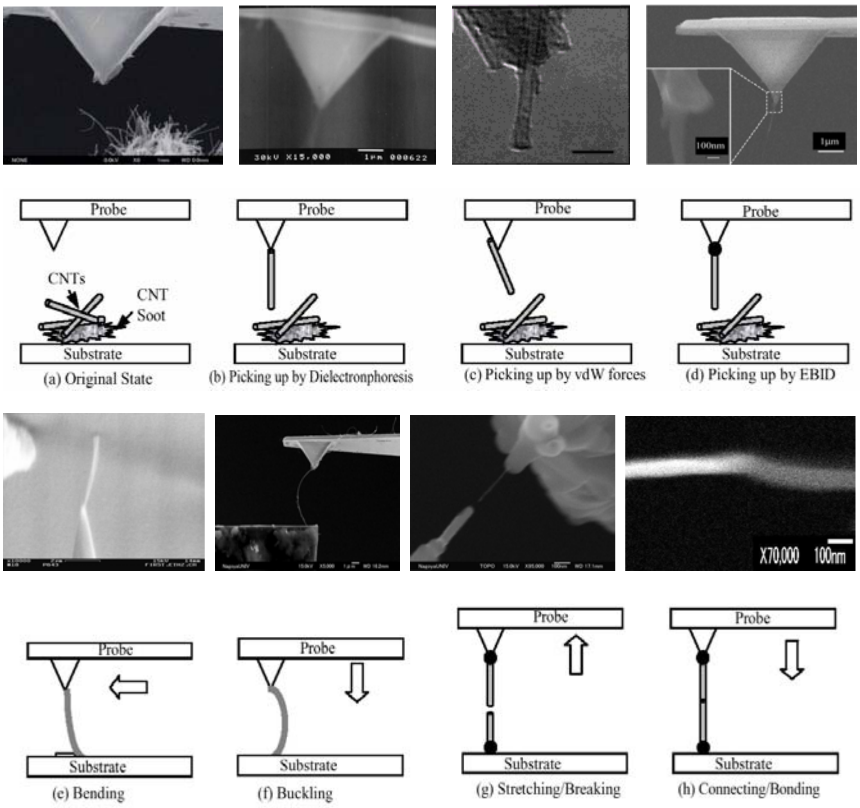


Fig. 3. Nanorobotic manipulation of CNTs. The basic technique is to pick up an individual tube from CNT soot (as in (a)) or from an oriented array; (b) shows a free-standing nanotube picked up by dielectrophoresis generated by a non-uniform electric field between the probe and substrate, (c) (from [14]) and (d) show the same manipulation by contacting a tube with the probe surface or fixing (e.g. with EBID) a tube to the tip. Vertical manipulation of nanotubes includes bending (e), buckling (f), stretching/breaking (g), and connecting/bonding (h). All examples with the exception of (c) are from the authors' work.

For detecting deep and narrow features on a surface, cantilevered nanotubes (Fig. 3(a), [15]) have been demonstrated as probe tips for an atomic force microscope (AFM) [16], a scanning tunneling microscope (STM) and other types of scanning probe microscopes (SPM). Nanotubes provide ultra-small diameters, ultra-large aspect ratios, and excellent mechanical properties. Manual assembly, direct growth and nanoassembly have proven effective for their construction. Cantilevered nanotubes have also been demonstrated as probes for the measurement of ultra-small physical quantities, such as femto-gram mass [17], mass flow sensors [18], and pico-Newton order force sensors [18] on the basis of their static deflections or change of resonant frequencies detected within an electron microscope. Deflections cannot be measured from micrographs in real-time limiting the application of these types of sensors. Inter-electrode distance changes cause emission current variation of a nanotube emitter and may serve as a candidate to replace microscope images [18].

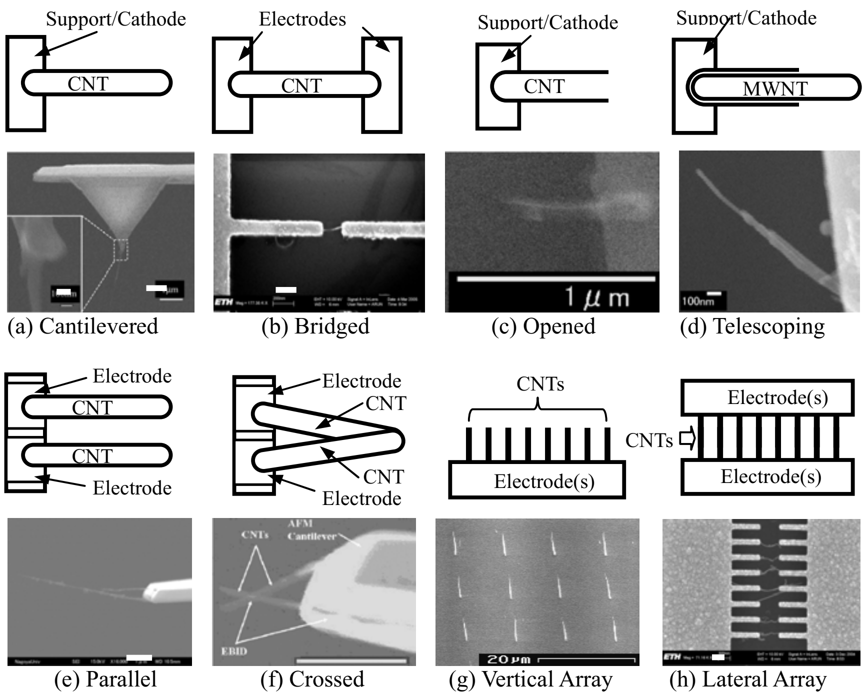


Fig. 4. Configurations of individual nanotube-based NEMS. Scale bars: (a) 1μm (inset: 100nm), (b) 200nm, (c) 1μm, (d) 100nm, (e) and (f)1μm, (g) 10μm, and (h) 300nm. All examples are from the authors' work.

Bridged individual nanotubes (Fig.3(b), [19]) have been the basis for electric characterization. A nanotube based gas sensor design has adopted this configuration [20].

Opened nanotubes (Fig.3(c), [21]) can serve as an atomic or molecular container. A thermometer based on this structure has been demonstrated by monitoring the height of the gallium inside the nanotube using transmission electron microscopy (TEM) [22].

Bulk nanotubes can be used to fabricate actuators based on charge injection induced bond-length change [23], and, theoretically, individual nanotubes also work on the same principle. Electro-static deflection of a nanotube has been used to construct a relay [24]. A new family of nanotube actuators can be constructed by taking advantage of the ultra-low inter-layer friction of a multi-walled nanotube. Linear bearings based on telescoping nanotubes have been demonstrated [25,18]. Recently, a micro actuator with a nanotube as a rotation bearing has been demonstrated [26]. A preliminary experiment on a promising nanotube linear motor with field emission current serving as position feed back has been shown with nanorobotic manipulation (Fig. 3(d), [21]).

Cantilevered dual nanotubes have been demonstrated as nanotweezers [27] and nanoscissors (Fig. 3(e)) [13] by manual and nanorobotic assembly, respectively.

Based on electric resistance change under different temperatures, nanotube thermal probes (Fig. 3(f), [18]) have been demonstrated for measuring the temperature at precise locations. These thermal probes are more advantageous than nanotube based thermometers because the thermometers require TEM imaging. The probes also have better reproducibility than devices based on dielectrophoretically assembled bulk nanotubes [28]. Gas sensors and hot-wire based mass/flow sensors can also be constructed in this configuration rather than a bridged one.

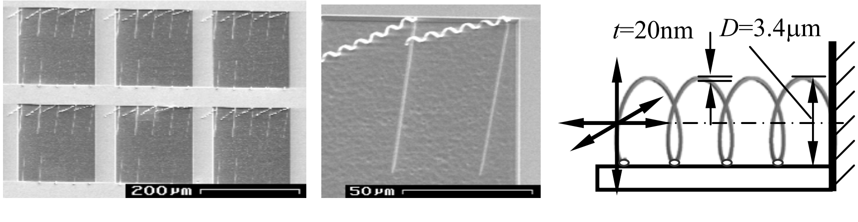
The integration of the above mentioned devices can be realized using the configurations shown in Fig. 3(g) [29] and (h) [12]. The arrays of individual nanotubes can also be used to fabricate nanosensors, such as position encoders [30].

Nanotube based NEMS remains a rich research field with a large number of open problems. New materials and effects at the nanoscale will enable a new family of sensors and actuators for the detection and actuation of ultra-small quantities or objects with ultra-high precision and frequencies. Through random spreading, direct growth, and nanorobotic manipulation, proto-types have been demonstrated. However, for integration into NEMS, self-assembly processes will become increasingly important. Among them, we believe that dielectrophoretic nanoassembly will play a significant role for large scale production of 2D regular structures [31].

IV. NEMS Made from Nanocoils

The construction of NEMS using nanocoils involves the assembly of as-grown or as-fabricated nanocoils, which is a significant challenge from a fabrication standpoint. Focusing on the unique aspects of manipulating nanocoils due to their helical geometry, high elasticity, single end fixation, and strong adhesion of the coils to the substrate for wet etching, a series of new processes is presented using a manipulator (MM3A, Kleindiek) installed in an SEM (Zeiss DSM962). As-fabricated SiGe/Si bilayer nanocoils are shown in Fig. 5. Special tools have been fabricated including a nanohook prepared by controlled “tip-crashing” of a commercially available tungsten sharp probe (Picoprobe T-1-10-1mm and T-1-10) onto a substrate, and a “sticky” probe prepared by tip dipping into a double-sided SEM silver conductive tape (Ted Pella, Inc.). As shown in Fig. 6, experiments demonstrate that nanocoils can be released from a chip by lateral pushing, picked up with a nanohook or a “sticky” probe, and placed between the probe/hook and another probe or an AFM cantilever (Nano-probe, NP-S). Axial pulling/pushing, radial compressing/releasing, and bending/buckling have also been demonstrated. These processes have shown the effectiveness of manipulation for the characterization of coil-shaped nanostructures and their assembly for NEMS, which have been otherwise unavailable.

Configurations of nanodevices based on individual nanocoils are shown in Fig. 7. Cantilevered nanocoils as shown in Fig. 7(a) can serve as nanosprings. Nanoelectromagnets, chemical sensors and nanoinductors involve nanocoils bridged between two electrodes as shown in Fig. 7(b). Electromechanical sensors can use a similar configuration but with one end connected to a moveable electrode as shown in Fig. 7(c). Mechanical stiffness and electric conductivity are fundamental properties for these devices that must be further investigated.



(a) Nanocoils (b) Model

Fig. 5 As-fabricated nanocoils (Thickness: t=20nm (without Cr layer) or 41nm (with Cr layer). Diameter: D=3.4μm)

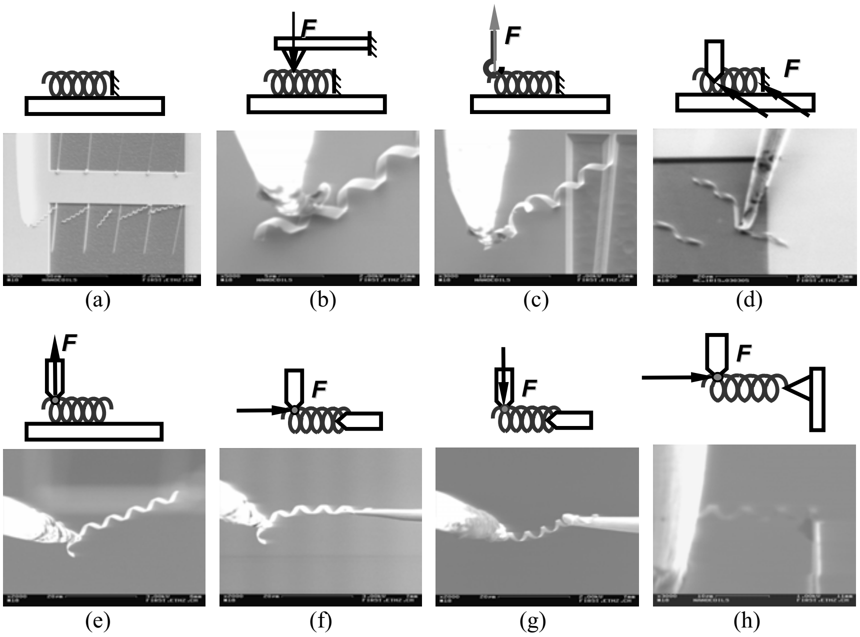
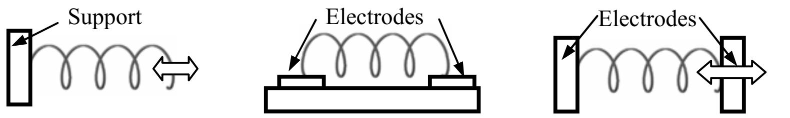
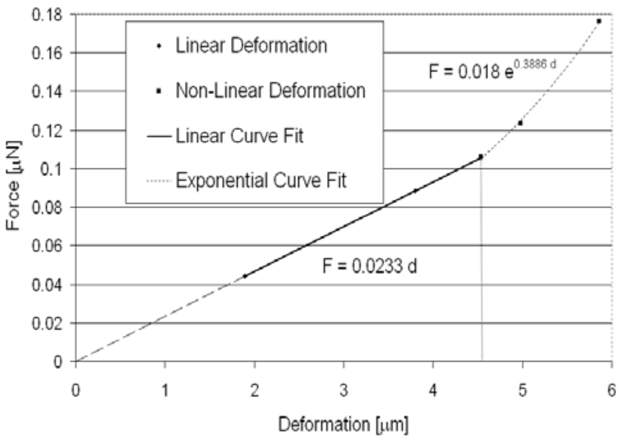


Fig. 6. Nanorobotic manipulation of nanocoils (a) original state, (b) compressing/releasing, (c) hooking, (d) lateral pushing/breaking, (e) picking, (f) placing/inserting, (g) bending, and (h) pushing and pulling

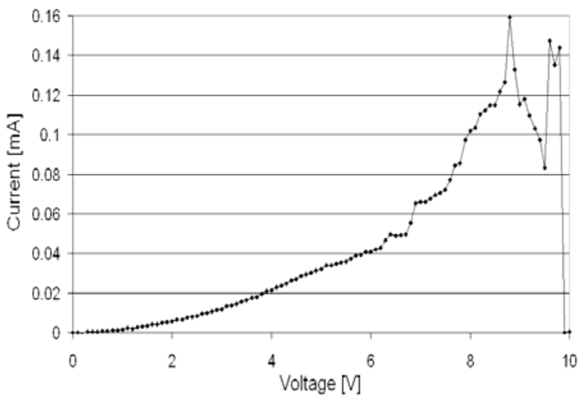
As shown in Fig. 6(h), axial pulling is used to measure the stiffness of a nanocoil. A series of SEM images are analyzed to extract the AFM tip displacement and the nanospring deformation, i.e. the relative displacement of the probe from the AFM tip. From this displacement data and the known stiffness of the AFM cantilever, the tensile force acting on the nanospring versus the nanospring deformation was plotted. The deformation of the nanospring was measured relative to the first measurement point. This was necessary because the proper attachment of the nanospring to the AFM cantilever must be verified. Afterwards, it was not possible to return to the point of zero deformation. Instead, the experimental data as presented in Fig. 7(d) has been shifted such that with the calculated linear elastic spring line begins at zero force and zero deformation. From Fig. 7(d), the stiffness of the spring was estimated to be 0.0233 N/m. The linear elastic region of the nanospring extends to a deformation of 4.5 μm. An exponential approximation was fitted to the nonlinear region. When the applied force reached 0.176 μN, the attachment between the nanospring and the AFM cantilever broke. Finite element simulation (ANSYS 9.0) was used to validate the experimental data [8]. Since the exact region of attachment



(a) Cantilevered (b) Bridged (fixed) (c) Bridged (moveable)



(d) Stiffness characterization of nanocoils



(e) I-V curve of a 11-turn nanocoil

Fig. 7. Nanocoil based devices. Cantilevered nanocoils (a) can serve as nanosprings. Nanoelectromagnets, chemical sensors, and nanoinductors use nanocoils bridged between two electrodes (b). Electromechanical sensors can use a similar configuration but with one end connected to a moveable electrode. Mechanical stiffness (d) and electric conductivity (e) are basic properties of interest for these devices.

cannot be identified according to the SEM images, simulations were conducted for 4, 4.5, and 5 turns to obtain an estimate of the possible range according to the apparent number of turns of the nanospring of between 4 and 5. The nanosprings in the simulations were fixed on one end and had an axial load of 0.106 μN applied on the other end. For the simulation results for the spring with 4 turns, the stiffness from simulation is 0.0302 N/m. For the nanospring with 5 turns it is 0.0191 N/m. The measured stiffness falls into this range with 22.0% above the minimum value and 22.8% below the maximum value, and very close to the stiffness of a 4.5-turn nanospring that has a stiffness of 0.0230 N/m according to simulation.

Fig. 7(e) shows the results from electrical characterization experiments on a nanospring with 11 turns using the configuration as shown in Fig. 6(g). The I-V curve is non-linear, which may be caused by the resistance change of the semiconductive bilayer due to ohmic heating. Another possible reason is the decrease in contact resistance caused by thermal stress. The maximum current was found to be 0.159 mA under an 8.8 V bias. Higher voltage causes the nanospring to "blow off." From the fast scanning screen of the SEM, an extension of the nanospring on probes was observed around the peak current so that the current does not drop abruptly. At 9.4 V, the extended nanospring is broken down, causing an abrupt drop in the I-V curve.

From fabrication and characterization results, the helical nanostructures appear to be suitable for inductors. They would allow further miniaturization compared to state-of-the-art micro inductors. For this purpose, higher doping of the bilayer and an additional metal layer would result in the required conductance. Conductance, inductance, and quality factor can be further improved if, after curling up, additional metal is electroplated onto the helical structures. Moreover, a semiconductive helical structure, when functionalized with binding molecules, can be used for chemical sensing under the same principle as demonstrated with other types of nanostructures [32]. With bilayers in the range of a few monolayers, the resulting structures would exhibit very high surface-to-volume ratio with the entire surface exposed to an incoming analyte.

V. Conclusions

A hybrid nanofabrication approach based on nanorobotic manipulation has been investigated for building NEMS. Processes for manipulating carbon nanotubes and SiGe/Si bilayer nanocoils have been developed, demonstrating their effectiveness for handling, structuring, and characterizing nanomaterials and nanostructures, and for assembling them into NEMS. An overview of NEMS made from individual nanotubes and nanocoils has been presented. A hybrid approach based on nanorobotic manipulation provides the possibility for *in situ* active property characterization, structuring and assembly of nanomaterials and nanostructures. The approach enables the construction of NEMS sensors and actuators and, eventually, nanorobots.

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