Nanorobotics for creating NEMS from 3D helical nanostructures

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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 3D SiGe/Si/Cr and Si/Cr nanostructures is presented. Nanosensors and nanoactuators are investigated from experimental, theoretical, and design perspectives.

1. Introduction

Three-dimensional helical structures with nanofeatures, such as carbon nanocoils, helical carbon nanotubes (CNTs) [1], and zinc oxide nanobelts [2] have attracted research interest because of their potential applications in nanoelectromechanical systems (NEMS). A new method of creating 3D helical structures with nanometer-scale dimensions has recently been presented [3] and can be fabricated in a controllable way [4] (Fig. 1). The structures are created through a top-down fabrication process in which a strained nanometer thick heteroepitaxial bilayer curls up (Fig. 1(a)) to form 3D structures with nanoscale features such as SiGe/Si tubes (Fig. 1(b), diameters between 10nm and 10µm), Si/Cr ring (Fig.1(c), see Ref. [5] for InGaAs/metal structures), SiGe/Si coils [4] (Fig.1(d)), InGaAs/GaAs coils [6] (Fig.1(e)), small-pitch InGaAs/GaAs coil (Fig.1 (f)), Si/Cr claws (Fig.1(g)), Si/Cr spirals [7] (Fig.1(h)), and small-pitch SiGe/Si/Cr coils [8] (Fig.1(i)). Because of their interesting morphology, mechanical, electrical, and electromagnetic properties, potential applications of these nanostructures in NEMS include nanosprings, electromechanical sensors, magnetic field detectors, chemical or biological sensors, generators of magnetic beams, inductors, actuators, and high-performance electromagnetic wave absorbers. Shrinking device size to these dimensions presents many fascinating opportunities such as manipulating nanoobjects with nanotools, measuring mass in fg ranges, sensing forces at pN scales, and inducing GHz motion, among other new possibilities waiting to be discovered. NEMS based on these 3D helical nanostructures are of increasing interest, indicating that capabilities for incorporating these individual building blocks at specific locations on a device must be developed.
Figure 1. 3D helical nanostructures (a) Schematic diagram of rolled-up helical structures. (b) SiGe/Si tube [4]. (c) Si/Cr ring. (d) SiGe/Si coil [4]. (e) InGaAs/GaAs coils [6]. (f) Small-pitch InGaAs/GaAs coil. (g) Si/Cr claws. (h) Si/Cr spiral [7]. (i) Small-pitch SiGe/Si/Cr coil [8].

Figure 2. A nanorobotic manipulation approach to NEMS. Nanorobotics (a) is a unique approach for functionalizing as-fabricated helical nanostructures (b) into NEMS (c) by changing their position/orientation (manipulation (d)), deforming their shapes (characterization (e)), modifying their structures (fabrication (f)), and increasing their numbers (assembly (g)).
Nanorobotic manipulation enables a hybrid approach by combining top-down and bottom-up processes for creating NEMS (Fig. 2) that can attain a higher functionality because they possess more complex structures. Because the as-fabricated nanostructures are not free-standing from their substrate, nanorobotic assembly is virtually the only way to incorporate them into devices at present. Moreover, for these structures, nanorobotic manipulation is still the only technique capable of in situ structuring and characterization. Moreover, property characterization can be performed after intermediate processes, and in situ active characterization can be performed using manipulation rather than conventional static observations. Nanorobotics expands the lower limit of robotic exploration further into the nanometer scale, and it will provide nanoscale sensors and actuators, structuring and assembly technology for building nanorobots. Nanorobotic manipulation is featured by multi-degrees-of-freedom and 3D processes, differentiating it from scanning probe techniques. Nanomaterial science, bionanotechnology, and nanoelectronics will also benefit from advances in this new nanomanufacturing technique from the perspectives of property characterization, fabrication and assembly.

2. Nanorobotic Manipulators and Tools
A nanomanipulator (MM3A™ from Kleindiek) installed inside a scanning electron microscope (SEM) (Carl Zeiss DSM962) is used for the experiments. The manipulator (as shown in Fig. 2 (a)) has three degrees of freedom, and 5 nm, 3.5 nm, and 0.25 nm resolution in X, Y, and Z directions at the tip, respectively. Each joint has a piezo-actuator with open-loop control. Kinematic analysis shows that when scanning in the X/Y directions using rotary joints, the additional linear motion in Z direction is very small. For example, when the arm length is 50 mm, the additional motion in the Z direction is only 0.25 nm to 1 nm when moving in the X direction for 5 µm to 10 µm; these errors can be ignored or compensated with the last prismatic joint, which has a 0.25 nm resolution.

The standard tool of the manipulator is a commercially available tungsten sharp probe (Picoprobe T-1-10-1mm (Fig. 3(a)) and T-1-10). To facilitate different processes, special tools have been fabricated including a nanohook (Fig. 3(b)) prepared by controlled “tip-crashing” of a sharp probe onto a substrate, and a “sticky” probe (Fig. 3(c)) prepared by tip dipping into a double-sided SEM silver conductive tape (Ted Pella, Inc.). AFM cantilevers (Nanoprobe, NP-S, Fig. 3(d)) are used for measuring forces or as electrodes.

Figure 3. Tools for Nanomanipulation. (b) Sharp tip. (c) Sticky probe. (d) Hook. (e) AFM cantilever

3. Configurations of NEMS
Configurations of NEMS based on 3D helical nanostructures are shown in Fig. 4. The cantilevered structures shown in Fig. 4(a, tubes, d, rings, g, coils, and j, spirals) can serve as nanosprings using their elasticity in axial (tubes and coils), radial (rings), and tangential/rotary (spirals) directions. Nanoelectromagnets, chemical sensors nanoinductors and capacitors involve building blocks bridged between two electrodes (two or four for rings) as shown in Fig. 4 (b, tubes, e, rings, h, coils, and k, spirals). Electromechanical sensors can use a similar configuration but with one end connected to a moveable electrode as shown in Fig. 4(c, tubes, f, rings, i, coils, and l, spirals). Mechanical stiffness and electrical conductivity are fundamental properties for these devices that must be further investigated. Electron microscopy imaging or their intrinsic electromechanical coupling property can serve as readout mechanisms.
Figure 4. Configuration of 3D helical nanostructures based NEMS. (a-c) Tubes. (d-f) Rings. (g-i) Coils. (j-l) Spirals. (a, d, g, j) Cantilevered. (b, e, h, k) Bridged (fixed). (c, f, i, l) Bridged (moveable).

4. Nanorobotic Manipulation for Creating NEMS

The construction of NEMS using 3D helical nanostructures involves the assembly of as-fabricated building blocks, which is a significant challenge from a fabrication standpoint. Focusing on the unique aspects of manipulating 3D helical nanostructures 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 the manipulator installed in an SEM. Processes are developed for the manipulation of as-fabricated 3D helical nanostructures. As shown in Fig. 5, experiments demonstrate that the as-fabricated nanostructures can be released from a chip by picked up with a “sticky” probe from their free ends (Fig. 5(a), tubes), fixed ends (Fig. 5(d), coils), external surfaces (Fig. 5(g), rings), or internal surfaces (Fig. 5(j), spirals), and bridged between the probe and another probe (Fig. 5(k) or an AFM cantilever (Fig. 5(b, e, h)), showing a promising approach for robotic assembly of these structures into complex systems. Axial pulling (Fig. 5(f1-4))/pushing, radial compressing (Fig. 5(i1-5)) /releasing, bending/buckling (Fig. 5(c1-4)), and unrolling (Fig. 5(l1-5), spirals; and Fig. 5(n1-8), claws) have also been demonstrated for property characterization. The stiffness of the tube, the coil and the ring has been measured from the SEM images by extracting the AFM tip displacement and the deformation of the structures. The stiffness of the tube, the ring, and the coil springs was estimated to be ~10N/m, 0.137 N/m, and 0.003 N/m (calibrated AFM cantilever stiffness: 0.038 N/m), showing a large range for selection. The linear elastic region of the small pitch coils reaches up to 90%. Unrolling experiments show these structures have excellent ability on memorizing their original shapes.

The excellent elasticity of nanocoils suggests that they can be used to sense ultra-small forces by monitoring the deformation of the spring as a “spring balance” (Fig. 5(f1-4)). If working in an SEM, suppose an imaging resolution of 1 nm can be obtained (the best commercially available FESEM can provide such a resolution in an ideal environment), a “spring balance” constructed with the calibrated coil (10turns, 0.003N/m) can provide a 3 pN/nm resolution for force measurement. With smaller stripe widths or more turns, nanocoils can potentially provide fN resolution. In the SEM used in these experiments, the available imaging resolution is 10nm, which provides a 30 pN/10 nm resolution. Fig. 5(f1-4) shows a way to use such a coil to measure the adhesive force between a coil and adhesive silver tape. Comparing the length difference, the extension of the spring can be found and converted to force according to the calibrated spring constant. For Fig. 5(f1-3), the relevant forces are determined to be 15.31±0.03 nN, 91.84±0.03 nN, (intermediate steps) and 333.67±0.03 nN (maximum holding/releasing force). It can be seen from Fig. 5(f4) that the coil recovered its shape after releasing.

Electrical properties can be characterized by placing a coil between two probes or electrodes [9]. An interesting phenomena found in the measurements is that the SiGe/Si nanocoils with Cr layers can shrink further by passing current through them or by placing a charged probe on them. A 5-turn as-fabricated coil was observed to become an 11-turn coil, showing the possibility of structuring them (Fig.1(f)).

These processes demonstrate the effectiveness of manipulation for the characterization of the 3-D helical nanostructures and their assembly for NEMS, which have otherwise been unavailable.
Figure 5. Nanorobotic manipulation of 3D helical structures. Pick up a tube (a), bridge it between a probe and an AFM cantilever (b), and buckle it (c1-4) for electromechanical property characterization for force measuring. Pick up a small pitch coil (d), bridge it between a probe and an AFM cantilever (e), and pull it for mechanical property characterization for building a “spring balance” (f1-4). Pick up a ring (External diameter: 12.56 μm. Strip width: 1.2 μm. Number of turns: 2.5. Thickness: Si/Cr 35 nm /10 nm) (g), bridge it between a probe and an AFM cantilever (h), and compress it for mechanical property characterization for understanding its stiffness (i1-5). Pick up a spiral (Si/Cr layer thickness: 35/10 nm) (j), bridge it between a probe and another probe (k), and unroll it for mechanical property characterization for understanding its interlayer interaction (taken from a video clip) (l1-5). Unroll a leaf of claws (m) for mechanical property characterization for understanding its “shape memory” (taken from a video clip) (n1-8).

5. Conclusions
A hybrid nanofabrication approach based on nanorobotic manipulation has been investigated for building NEMS. Processes for manipulating 3D helical nanostructures have been developed, demonstrating their effectiveness for handling, structuring, and characterizing as-fabricated nanostructures, and for assembling them into NEMS. 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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