Hybrid Nanorobotic Approaches for Fabricating NEMS from 3D Helical Nanostructures

Lixin Dong\textsuperscript{1}, Li Zhang\textsuperscript{2}, Dominik J. Bell\textsuperscript{1}, Bradley J. Nelson\textsuperscript{1}, and Detlev Grützmacher\textsuperscript{2}

\textsuperscript{1} Institute of Robotics and Intelligent Systems
\textsuperscript{2} Laboratory for Micro- and Nanotechnology

ETH Zürich
Paul Scherrer Institute

ETH-Zentrum, CH-8092, Zürich, Switzerland
Villigen-PSI, CH-5232, Switzerland

ldong, dbell, bnelson@ethz.ch
li.zhang, detlev.gruetzmacher@psi.ch

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 SiGe/Si/Cr nanocoils and Si/Cr nanospirals is presented. Nanosensors and nanoactuators are investigated from experimental, theoretical, and design perspectives.

Index Terms - Nanorobotics, nanomanipulation, nanoassembly, NEMS, 3D helical nanostructures

I. INTRODUCTION

Three dimensional helical structures with nanofeatures, such as nanocoils, helical carbon nanotubes (CNTs), zinc oxide nanobelts and other helical semiconductive nanostructures [1], have attracted research interest because of their potential applications in nanoelectromechanical systems (NEMS) as springs, electromagnets, inductors, resonators, sensors, and actuators [2, 3]. These 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 nanobjects 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 microelectromechanical systems (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.

Top-down and bottom-up nanofabrication strategies are being independently investigated by various researchers. Top-down approaches (Fig. 1(a)) are based on nanofabrication and include technologies such as nanolithography, nano-imprinting, and chemical etching. Presently, these are 2D fabrication processes with relatively low resolution. Bottom-up strategies (Fig. 1(b)) 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 [4].

By combining top-down and bottom-up processes, a hybrid nanorobotic approach (Fig. 1(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.

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 nanocoils and nanospirals in Section II. In Sections III, manipulators and tools are introduced. Basic processes of manipulation are developed and demonstrated in Section IV. The applications of these processes in property characterization, structuring and assembly of NEMS are then presented in Sections V, VI and VII.

II. 3D HELICAL NANOSTRUCTURES

Nanocoils and nanospirals have been used as base materials and structures for NEMS because of their exceptional properties and unique structures. 3-D helical nanostructures have been synthesized from different materials including helical carbon nanotubes [5] and zinc oxide nanobelts [6]. A new method of creating structures with nanometer-scale dimensions has recently been presented [1] and can be fabricated in a controllable way [7] (Fig. 2(a), (b)). SiGe/Si nanotubes with diameters between 10nm and 10μm have been achieved. Recently, a simple way to fabricate micro- and nanotubes has been reported based on strained semiconductor-metal (e.g. InGaAs/metal) double layers [8]. In Si/ Cr bi-layers it has been observed that when the stripe width decreases (from 3.0 μm to 0.5 μm), the scrolling direction of the Si/Cr stripe gradually changes from the <100> direction to the longitudinal axis of the stripe. Moreover, after the ring structure forms, the diameter of the Si/Cr rings decreases with decreasing stripe width (1.20 μm to 0.20 μm). Based on this width effect, freestanding Si/Cr spirals have been successfully fabricated [9] (Fig. 2(c), (d)). The Si/Cr “Siemensstern” pattern (wagon wheel [10]) shown in Fig. 2(d) suggests the possibility of integrating such structures into NEMS. 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. Because of their interesting morphology, mechanical, electrical, and electromagnetic properties, potential applications of these nanostructures in NEMS include nanosprings [3], electromechanical sensors [2], magnetic field detectors, chemical or biological sensors, generators of magnetic beams, inductors, actuators, and high-performance electromagnetic wave absorbers. NEMS based on nanocoils and nanospirals are of increasing interest, indicating that capabilities for incorporating these individual building blocks at specific locations on a device must be developed.

For carbon nanotubes, random spreading, direct growth, self-assembly, dielectrophoretic assembly and manipulation [11, 12] have been demonstrated for positioning as-grown materials on electrodes for the construction of similar devices. Because the as-fabricated nanocoils and nanospirals 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.

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

![Image](image1)

(a) MM3A  
(b) Sharp tip  
(c) Sticky probe  
(d) Hook  
(e) AFM cantilever

Fig. 3. Nanomanipulator (MM3A™ from Kleindiek) and tools

IV. BASIC PROCESSES FOR NANOROBOTIC MANIPULATION

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 the manipulator installed in an SEM. Processes are developed for the manipulation of as-fabricated SiGe/Si bilayer nanocoils (Thickness: \(t=20\text{nm}\) (without Cr layer) or 41nm (with Cr layer). Diameter: \(D=3.4\mu\text{m}\)) and Si/Cr nanospirals (Thickness: a 35 nm thick Si layer and a 10 nm Cr layer) as shown in Fig. 2(b) and (c), respectively, or as shown schematically in Fig. 4.

![Image](image2)

(a) Model of nanocoils  
(b) Model of nanospirals

Fig. 4 As-fabricated nanocoils and nanospirals

![Image](image3)

(a) Original state  
(b) Compressing/releasing  
(c) Hooking  
(d) Lateral pushing/breaking  
(e) Picking  
(f) Placing/inserting  
(g) Bending  
(h) Pushing and pulling

Fig. 5. Nanorobotic manipulation of nanocoils

As shown in Fig. 5, 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. Axial pulling/pushing, radial compressing
/releasing, and bending/buckling have also been demonstrated. Processes for manipulating nanospirals are shown in Fig. 6 including picking up by attaching a “sticky” probe to the external surface or internal one, transfer to other locations, transfer a spiral to another probe and radial/axial position adjustment. 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.

![Nanorobotic manipulation of nanospirals](image)

V. CONFIGURATIONS OF NEMS

Configurations of NEMS based on nanocoils and nanospirals are shown in Fig. 7. The cantilevered nanocoils 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). Similar configurations for nanospirals are shown in Fig. 7(d), (e), and (f) simply by changing the prismatic motion into rotation. Mechanical stiffness and electric conductivity are fundamental properties for these devices that must be further investigated.

![Configuration of 3D helical nanostructures based NEMS](image)

VI. PROPERTY CHARACTERIZATION

Nanorobotic manipulation provides fundamental techniques for the characterization of helical nanostructures. Axial pulling (Fig. 5(h)) 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. 8 has been shifted such that with the calculated linear elastic spring line begins at zero force and zero deformation. From Fig. 8, 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 [3]. Since the exact region of attachment 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 is very close to the stiffness of a 4.5-turn nanospring that has a stiffness of 0.0230 N/m according to simulation.

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. 9). 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 a calibrated coil (10 turns, 0.003 N/m) can provide a 3 pN/nm resolution for force measurement. With smaller stripe widths or more turns, nanocoils can potentially provide femto-Newton resolution. In the SEM used in these experiments, the available imaging resolution is 10 nm, which provides a 30 pN/10 nm resolution. Fig. 9 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. 9 (b) to (d), 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. 9(e) that the coil recovered its shape after releasing.

The as-fabricated Si/Cr spirals are manipulated for characterizing elasticity. Fig. 10 shows a sharp probe (Picoprobe T-1-10-1mm) mounted on the manipulator approaching a spiral nanobelt and being inserted into the spiral (Fig. 4 inset). To investigate the flexibility of the spiral belts, the probe is used to extend them as shown in Fig. 11, where a spiral is completely extended along its longitudinal axis and subsequently recovers to its original shape after being released from the extension (Fig. 11 (d)). No significant change in its curvature due to the extension was observed, which indicates that these freestanding spirals have a strong “memory” of their shape after being formed.

The radial stiffness of a helical structure can be characterized by radial pushing and/or pulling. A Si/Cr ring as shown in Fig. 12 has been used as a test structure. The ring is formed with a similar process for making spiral nanobelts but with a rectangular strip. Its stiffness in the radial direction was
found to be 0.108 N/m by pushing it onto an AFM cantilever (calibrated stiffness: 0.03 N/m) as shown in Fig. 13.

![Fig. 13. Radial stiffness of a ring.](image)

Electrical properties can be characterized by placing a coil between two probes or electrodes. Fig. 14 is an I-V curve of a coil (inset). 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. As shown in Fig. 15(a), the section of a coil between two probes shrinks after the upper probe is attached to the coil, where the inset shows the original state after being picked up. Fig. 15(b) shows the coil after removing the upper probe. The difference of the coil diameters can be seen in the inset. Whereas the mechanism is still not well understood, the reproducibility in all four coils investigated shows that this can be a structuring process of the coils for making thinner coils with more turns than as-fabricated ones, which in turn provides less strict requirements on stripe width. A 5-turn as-fabricated coil was observed to become an 11-turn coil.

### VII. Conclusions

A hybrid nanofabrication approach based on nanorobotic manipulation has been investigated for building NEMS. Processes for manipulating SiGe/Si/Cr nanocoils and Si/Cr nanospirals have been developed, demonstrating their effectiveness for handling, structuring, and characterizing nanomaterials and 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.

### References


