Rolled-up helical nanobelts: from fabrication to swimming microrobots

Li Zhang and Bradley J. Nelson
Institute of Robotics and Intelligent Systems, ETH Zurich, Tannenstrasse 3, Zurich, CH 8092, Switzerland

ABSTRACT

We present recent developments in rolled-up helical nanobelts in which helical structures are fabricated by the self-scrolling technique. Nanorobotic manipulation results show that these structures are highly flexible and mechanically stable. Inspired by the helical-shaped flagella of motile bacteria, such as E. coli, artificial bacterial flagella (ABFs) are a new type of swimming microrobot. Experimental investigation shows that the motion, force, and torque generated by an ABF can be precisely controlled using a low-strength, rotating magnetic field. These miniaturized helical swimming microrobots can be used as magnetically driven wireless manipulators for manipulation of microobjects in fluid and for target drug delivery.

INTRODUCTION

Microfabrication of helical structures is difficult for lithography-based techniques due to lithography’s inherent 2-D patterning. Previously, a number of nanohelix fabrication methods have been developed based on “bottom-up” approaches [1-3]. Recently, a strategy that combines “top-down” and “bottom-up” approaches for fabricating 3D micro-/nanostructures has been introduced [4-5]. This method is based on the coiling of strained 2D thin films to form 3D structures after the films detach from the substrate by selective etching, a type of self-assembly. Diverse 3D micro-/nanostructures have been achieved, such as tubes [4-6], helices [4, 7-8], micro-origami [9-11] and wrinkles [12-13]. It was found that rolled-up helical nanobelts can be designed with a specific geometrical shape, i.e., their diameter, chirality, pitch, helicity angle and length can be precisely controlled [14-15]. The as-fabricated helical nanobelts are highly flexible and retain a strong “memory” of their original shape [16-20]. Because of their interesting morphology and mechanical and electromagnetic properties, potential applications of these helical nanobelts include force sensors, chemical and biological sensors, inductors, and actuators. Inspired by the natural bacterial flagellum [21-23], we have developed helical swimming microrobots driven by a rotating magnetic field [24-26]. These miniaturized devices can be used as wireless manipulators for medical and biological applications in fluid environments, such as cell manipulation and removal of tissue. Due to its large surface to volume ratio, surface functionalized ABFs have the potential to sense and transmit inter- or intracellular information, and to perform targeted drug delivery.

EXPERIMENT

The fabrication of rolled-up helical nanobelts is illustrated schematically in Fig. 1. Bilayer or multi-layer thin films are deposited on a single crystal wafer, such as Si or GaAs, after the deposition of a sacrificial layer. The hetero-films are grown and patterned to a ribbon-like mesa by lithography. The ribbon is then detached from the substrate by selective wet etching of
the sacrificial layer and forms a helical nanobelt to relieve internal stress. A more straightforward approach is to deposit hetero-films on a substrate with etching selectivity. Therefore, the coil structure can be obtained by directly etching the substrate [7]. Fabrication details are reported in Ref [14-17].

A nanomanipulator and an AFM cantilever built in an SEM were used for the stretching test of individual helical nanobelts [17-20]. The manipulation processes were conducted as follows: a tungsten probe on the manipulator was first dipped into a silver tape to make its tip sticky. This probe was used to cut a helical nanobelt with one fixed end from the substrate and then to pick it up. Next, the free end of the spring was clamped onto an AFM cantilever using electron-beam-induced deposition (EBID). After the helical nanobelt was fixed between the probe and the AFM cantilever, as shown in figure 2, a tensile force was applied by moving the probe away from the AFM cantilever to investigate the spring constant of the helical nanobelt. Resonance frequency tests of a helical nanobelt were conducted using electrostatic actuation between a tungsten wire and the helical nanobelt [17].

Figure 1. The flowchart for fabricating a rolled-up helical nanobelt on a (001)-oriented substrate. The red arrow indicates the scrolling direction of the nanobelt, i.e. [100].

Figure 2. The nanorobotic manipulation of rolled-up helical nanobelts for characterizing flexibility and the spring constant. The scale bars are 5 μm.
An ABF consists of two parts, a helical nanobelt tail resembling a natural bacterial flagellum in both size and shape and a soft-magnetic metal head [24-25]. To actuate and control the swimming of the helical swimming microrobots wirelessly in water, three pairs of orthogonal electromagnetic coils were applied which are able to generate a uniform rotating magnetic field that exerts a torque on the head of the ABF, causing the ABF to rotate.

DISCUSSION

Controlled fabrication

Our fabrication results revealed that when the width of hetero-films is in the micrometer range or larger the scrolling direction for Si-based and GaAs-based strained films is determined by the smallest Young’s modulus direction, e.g. <100> in the case of (001)-oriented substrate. Therefore, controlled fabrication of helices can be achieved, which means that the chirality, the helicity angle and the pitch of helices can be precisely controlled by the 2D ribbon-like mesa design. When the ribbon width is shrunk to the submicron and nanometer range, new effects from the edges of the ribbon cause the anomalous coiling of the nanohelices and strongly influence the shape of the rolled-up nanostructure. For example, experimental results showed that when the ribbon width is reduced to 300 nm for a 20 nm thick SiGe/Si bilayer, the effect of stress relaxation at the edges of the ribbon, rather than the Young’s modulus, dominate the scrolling process (see Fig. 3). Stress relaxation leads to a uniaxial strain component along the long axis of the ribbon. Based on this anomalous coiling principle, nanocoils with small helical angles and pitches have been achieved, which exceeds the 45° limitation dictated by the preferred <100> scrolling direction for micrometer scale helices [14-15]. Depositing a metal layer on the bilayers can also be used to tailor the shape of the nanostructure. Our new findings of the anomalous coiling principle have provided additional design and fabrication opportunities to create 3D nanostructures.

Figure 3. SEM micrographs of Si_{0.6}Ge_{0.4}/Si (11/8 nm) helical nanobelts with the same deviation of 5° from <110>. The ribbon width in (a) to (d) is 1.30 μm, 1.20 μm, 0.40 μm and 0.30 μm, respectively. All the images have the same magnification. Inset in (c) shows an SEM micrograph of an anomalous coiled SiGe/Si/Cr helical nanobelt with small pitch. Inset in (d) shows an SEM micrograph of a Si/Cr microspiral.

Mechanical properties

Tensile tests were performed for SiGe/Si/Cr and InGaAs/GaAs helical nanobelts and show that they are highly elastic and behave like micro-springs (see Fig. 4) with spring constants in a range of 3-20 pN/nm [17-20]. By tuning design parameters, i.e. the number of turns, the thickness of the wall, the width and orientation of the stripe, the diameter and the pitch of a
helical spring, a desired stiffness can be obtained through simulation. Resonance tests of the helical nanobelts, both in the bending mode and in the axial displacement mode, indicated that the mechanical properties of the bilayer material do not change over $10^6$ loading cycles [17].

Figure 4. Spring constant characterization of a SiGe/Si/Cr helical nanobelt. According to the linear range of the elongation-load curve, the spring constant of the helical nanobelts is 0.003 N/m [18]. All SEM micrographs have the same scale bar.

Swimming behavior of ABFs

In 1973, it was discovered that some bacteria such as E. coli swim in liquid by turning the base of a flagellum or a bundle of flagella [21]. Unlike E. coli, which uses 45 nm diameter molecular motors for actuation [22], the ABF was actuated by a uniform rotating magnetic field. A magnetic torque is applied on the soft magnetic head to rotate the ABF along its helical axis and to steer it in liquid. Due to the helical nanobelt tail, the ABF is self-propelled somewhat similar to a corkscrew motion [23]. The results showed that these helical swimming microrobots can be steered in 3-D with micrometer positioning precision as shown in Fig. 5 [24]. Swimming tests of ABFs showed a linear relationship between the frequency of the applied field and the translational velocity when the frequency is lower than the step-out frequency of the ABF [25]. Moreover, the propulsive force and the applied torque can be estimated and tuned over a large range by changing the input field once the propulsion matrix is experimentally determined [25]. We calculated the maximum force and the applied torque generated by a 38 μm long ABF [25]. It was found that with a 2 mT magnetic field a maximum force of 3.0 pN is sufficient to move a microscale object such as a blood cell. The maximum torque is 43 nN·nm, which is ca. two orders of magnitude larger than that of the molecular motor in E. coli [22].

Figure 5: A 38 μm long ABF swims towards a target (dark dot) controlled by a rotating magnetic field [24].

Micromanipulation using ABFs

Self-propelled ABFs can provide a versatile tool for manipulating cellular or sub-cellular objects [26]. In principle, two different manipulation methods could be applied: (i) Contact manipulation, in which ABFs contact the microobjects and manipulate them directly. (ii) Noncontact manipulation, in which ABFs manipulate the microobjects by generating a controlled fluid flow. Contact manipulation, such as pushing and rotating (see Fig. 6), were discussed
earlier [24]. For a manipulation task such as drilling biological membranes and drug delivery into a cell, the small cross-sectional area of the ABF has the advantage of applying a relatively large pressure. For noncontact manipulation, the fluid flow generated is able to pump microobjects to one side of the ABF simultaneously, once the boundary condition of the swimming ABF is inhomogeneous around the ABF [26].

Figure 6: Two 6 μm diameter polystyrene (PS) microspheres are rotated by a 29 μm long ABF [24].

CONCLUSIONS

In summary, the self-scrolling technology is promising for controlled fabrication of helical nanobelts, which have potential applications in MEMS/NEMS devices and wirelessly controlled swimming microrobots. Once functionalized, ABFs have the potential to perform as sensors for inter- or intracellular information sensing and to perform targeted delivery of energy (e.g., inductive heating) and chemical and biological substances. ABFs also have the potential to be used as in vivo medical micro/nanorobots. However, biocompatibility of the materials, tracking, and navigation of the robots in a dynamic fluidic environment remain a challenge.

ACKNOWLEDGMENTS

The authors thank the FIRST lab and EMEZ at ETH Zurich and the Laboratory for Micro- and Nanotechnology at the Paul Scherrer Institute for microfabrication and characterization support. The authors are grateful to Prof. Detlev Gruetzmacher (RWTH Aachen), Prof. Lixin Dong (Michigan State University), Prof. Jake J. Abbott (University of Utah), Dr. Dominik Bell (ETH Zurich), Dr. Bradley E. Kratochvil (ETH Zurich) and Kathrin E. Peyer (ETH Zurich) for their contributions. Funding for this research was partially provided by the Swiss National Science Foundation (SNSF).

REFERENCES