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Helices in micro-world: Materials, properties, and applications

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Abstract

The demand for equipments with small dimensions and high performance as well as the development of micro-/nano-fabrication has stimulated intensive researches related to micro-/nano-structures. As a new member in the micro-world with three-dimensional geometry, micro-helices made from various materials possess unique properties and meanwhile present challenge in fabrication. This overview reviews recent progresses in micro-helices related researches, especially fabricated by rolled-up nanotechnology. The fabrication approaches with respective advantages and limitations are summarized and categorized, and the underneath mechanisms are explained. The important properties related to the helical geometries in the disciplines of mechanics, electrics, magnetics, and optics are discussed in detail. The results summarized here suggest that micro-helices may have great potential in micro-devices and systems like micro-electro-mechanical system and lab-on-a-chip.

Keywords: Micro-helix; Materials; Fabrication; Properties; Applications

1. Introduction

Mathematically, an ideal helix curve has the property that the tangent line at any point makes a constant angle with a fixed line called the axis [1]. One should notice that the nature has already built plenty of sophisticated helical structures, although the structures may not as perfect as the definition from mathematics. Seashells, horns, plant tendrils, and seed pods are macroscopic examples [2]. The important genetic material-DNA molecule, which consists of two helical chains each coiled round the same axis, is a representative in the micro-world. Helix-related structures can also be frequently noticed in the ordinary life. For instance, a helical spring with structural flexibility, is a mechanical device used to store energy due to resilience and release, and therefore can be engaged to absorb shock, or to maintain a force between contacting surfaces [3]. Another example is the screw. The thread on its body surface is obviously a helix-like structure, which has the ability to transfer the rotation into the motion along the axis direction. Nowadays, fabrication of artificial helices with different materials in the macro-world may not be very difficult due to the rapid development of industrial technique; however, producing a helix in micro- or nano-world is more challenging.

Recently, it is increasingly demanded for equipments with small dimensions and high performance. The typical example is the well-known Moore's law. Similar demands also motivate the researches in the interdisciplinary fields such as micro/nano-electro-mechanical systems (MEMS/NEMS) and lab-on-a-chip. The enormous progresses in the miniaturization of those electronic, optical and mechanical devices have led to intense studies of fabrication methods and physical properties of the corresponding building blocks, i.e. micro-/nano-structures and materials. The helices in micro-/nano-scale are still a three-dimensional structure although the dimensions are much smaller than their macro counterparts. This three-dimensional geometry certainly implies difficulty in manufacturing,

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because the structures are too big to be made by well-established molecular synthesis, and too small to be constructed by the tools and methods used in the macro case [4]. On the other hand, the unique geometry in small dimension may give birth to a lot of new properties, and may find advantageous applications in electronics, optoelectronics, sensing and actuating, and electromechanically coupled devices [4]. More and more interest has been attracted, while the number of the publications in the related disciplines increases rapidly.

From the viewpoint of practical applications, the helices in the micro-scale (typical dimension from ~100 nm to ~100 μm) are important and interesting. For instance, due to their relative larger size, their incorporation into MEMS is direct and the characterization can be carried out in a convenient way, since most micro-structures are visible in normal optical microscope. The devices sometimes can even be built up by hand. The helices in nano-scale, on the contrary, are even difficult to be fabricated and investigated, although the new sciences in such small scale may suggest even significant potentials in the future. Based on this consideration, here, we mainly focus on the fabrications of the helices and related structures with the diameter from ~100 nm to ~100 μm. The fabrication of micro-helices from different materials will be categorized and their novel properties and applications will be summarized and reviewed. Given limited space, priority will be given to new and unique approaches and properties. Our emphasis is artificial helical micro-structures, the helicity from the molecules and their arrangement like in liquid crystal [5] will not be covered.

2. Fabrication techniques and mechanisms

There are a few methods commonly used in micro-fabrications, and they are classified to two groups: "top-down" and "bottom-up". The top-down approaches create micro-structures by shaping the larger materials into the desired structures while the bottom-up approaches try to make smaller components built up into complex assemblies. Generally, a specific method can be evaluated according to its generality, tunability, and controllability. In this section, we will summarize the methods used in producing micro-helices. Both "top-down" and "bottom-up" approaches will be discussed.

2.1. Self-assembly in vapor phase deposition

Vapor phase deposition generally consists of vapor transport and vapor reaction at suitable temperature and pressure [6]. There are actually different mechanisms and reactions taking place in the processes, making the method capable of produce abundant microstructures.

Carbon nanotube (CNT) is an important nanomaterials and its discovery in 1991 inspires researches in carbon-related materials [7,8]. CNT and carbon nanowire (CNW) can be produced by chemical vapor deposition (CVD) via a vapor−liquid−solid (VLS) process: the carbon formed in the gas phase is dissolved in a molten catalyst droplet (liquid) and reaches oversaturation. The liquid nucleates at lower temperature to form CNT or CNW (solid) at the droplet/substrate interface. Under certain experimental conditions, CNT or CNWs with helical geometry were obtained. Publications based on individual results reported carbon-related helices with different dimensions and crystallinity [4,9,10]. A typical scanning electron microscopy (SEM) image of an array of highly aligned helical CNTs with nearly identical diameter and pitch is shown in Fig. 1(a) [11]. The mechanism for this curved growth process is believed to be connected with the growth front, i.e. the carbon/catalyst interface. Several models have been proposed but no consistence has been achieved. The first model suggests the regular insertion of pentagon−heptagon pairs at the interface and the stress introduced cause the unique geometry [12−15]. The second model invokes the localized stresses and anisotropic deposition rates on

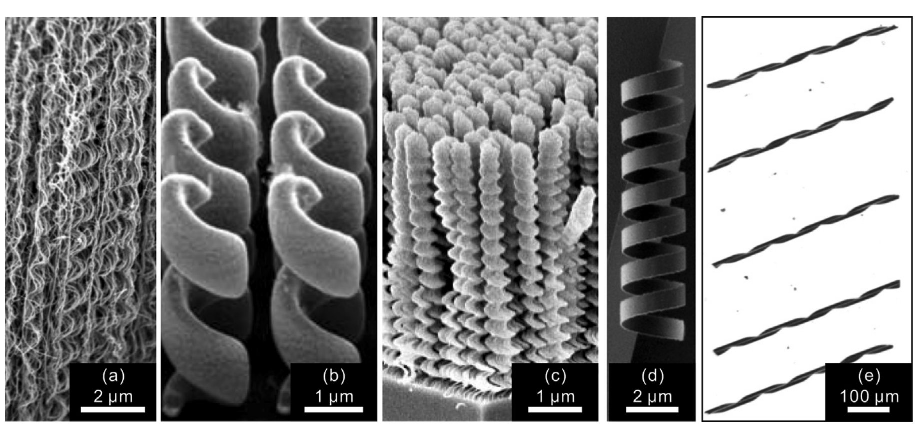

Fig. 1. (a) SEM image of an array of helical CNTs with identical diameter and pitch. Adapted with permission from Ref. [11]. (b) Oblique view of the helical structures after removal of the template. Adapted with permission from Ref. [28]. (c) Morphology of MgF_2 micro-helices on glass with 15 turns. Adapted with permission from Ref. [37]. (d) Micro-helix fabricated by rolling SiGe/Si/Cr multi-layered nanomembrane. Adapted with permission from Ref. [63]. (e) Optical image of an array of grating-structured micro-helices.

faceted catalyst droplets [16,17]. The third model explains the phenomenon by considering the different wettabilities/contact angles at the interface [11,18]. The last model is actually not limited to CNT systems. Researchers believed that this model can explain why other materials like SiC or SiO_2 also forms micro-helix in a VLS process [19−21].

A slightly different vapor−solid (VS) process was reported to produce single-crystal Si_3N_4 [22], InP [23], and ZnO micro-helices [24−26]. Among them, ZnO micro-helices are extensively investigated. The wurtzite-structured ZnO are a number of alternating planes composed of tetrahedrally coordinated O^{2-} and Zn^{2+} ions that are stacked alternatively along the c axis. This structure produces positively charged Zn (0001) and negatively charged O (000-1) surfaces, resulting in a normal dipole moment and spontaneous polarization along the c axis [25]. The ZnO belt formed in the VS process with this polarization normal to the belt has the tendency to curve into a helical structure as a consequence of minimizing the total energy contributed by spontaneous polarization and elasticity [24−26]. The key point here is to produce the polarization, i.e. the higher-energy {0001} surface, and Gao and Wang [24] mentioned the tuning of experimental parameters could be crucial. A pre-pumping step would reduce the possibility of gaseous molecular adsorption onto the {0001} polar surfaces, which consequently promote the productivity of the ZnO helices [24]. The same group also found that the electrostatic may not be directly balanced by bending the ZnO belt. If the width of the belt is rather large, forming superlattice-structured stripes with opposite polarization is a possible way to reducing electrostatic energy [27]. Thus, the accumulation of rigid structural rotation or twist across the width of the superlattice belt and a continuous growth of the stripes consequently leads to the formation of a helical structure [27].

In general, the vapor phase deposition is commonly used to produce some semiconductor structures with high crystal quality. However, as a high temperature process, it is therefore not suitable for producing micro-helix on soft substrate like plastics. In addition, the self-assembly nature makes the process less controllable, which is obviously inconvenient for device fabrication.

2.2. Template-assisted synthesis

Template-assisted approach is quite common in micro- and nano-fabrications. Based on the template used, e.g. positive or negative type, the required material is deposited onto or filled into the template to form a positive or negative replica. Since the obtained structure well reproduces the template, the geometry of the resulting structure is determined by the predefined template. Although the template-assisted synthesis normally implies more steps, perfect micro-structures could be fabricated if a good template is employed. The method in general enables good control over the geometrical dimensions and a wide range of materials can be deposited.

As for the fabrication of micro-helix, an ordinary template can be made from photoresist. In positive-tone resist, only those regions that are exposed by light are removed in the development process. Gansel et al. [28] used three-dimensional direct laser writing (DLW) system to produce helical air void in positive-tone resist (negative template), and then electrochemically deposited metal (e.g. Au) into the void. The deposition process can be effectively tuned by monitoring the current density. Finally, the resist was removed by plasma after deposition, leaving freestanding micro-helix array on the substrate, as shown in Fig. 1(b). One the other hand, if negative-tone resist is used in the DLW process, helical structure made of the resist is left after the development process [29,30]. The active layer is then coated on the surface of the resist helix forming the final product.

The introduction of the DLW in template fabrication provides the capability to create helical structures of various designs and materials. However, this needs special and expensive equipment and other cheaper templates may also be used. Porous anodic alumina membrane with highly ordered diameter-tunable channels can confine the chemical or physical reaction to a specific position, thereby allowing the efficient production of micro- and nano-structures. By engaging this template, researchers have co-deposited Pd and Cu electrochemically into the channels forming metallic rods [31]. Under certain experimental conditions, the Pd helix can be obtained and clearly observed after the removal of Cu. It was found that due to the composition of the alumina surface, the metallic ions are reduced there. And the key requirement for Pd helix synthesis is the appropriate composition of Pd and Cu ions [31]. The deposition rates of Pd and Cu are significantly influenced by their different chemical activities, and under a suitable deposition rate, the screw dislocation in Pd grain can trigger the propagation of atom growth preferentially on the steps of a crystal surface in a spiral fashion [31,32], leading to the formation of Pd micro-helix. In fact, the template may even be found in the nature, where many unique and complex shapes are present beyond any current technologies for artificial production. For instance, metallic helix has been prepared by plating Ag on the surface of spiral vessel from vascular plant. The detailed process of obtaining spiral vessel was presented in Ref. [33]. Obviously, these templates are cheaper and can be obtained conveniently, but the geometries of the resultant helices may not be perfect with less tenability compared with those made by using DLW templates.

It is worth noting that deposition of active materials needs special concern to ensure an accurate reproducing process. In the case of negative template, an immersion of template in gaseous CO_2 prior to deposition in solution can remove the air bubble in the template which may inhibit the wet chemical process [34]. If the material is deposited in vapor phase, e.g. evaporation, shadow effect may exist, leading to an imperfect coating [30]. In such case, a conformal coating process like electroless plating would be better [29].

2.3. Glancing angle deposition

The glancing angle deposition (GLAD) method can be used to prepare micro-helix and related structures with the help of substrate rotation. The technique is actually an extension of the commonly used oblique angle deposition where the deposition flux is incident onto a substrate at a large incident angle α (typically $\alpha > 75°$) with respect to the substrate normal [6,35–38]. Under the parameters of such a glancing angle α, local film growth variations lead to strong shadowing effect and competition between nucleating grains [38]. The flux is intercepted by the high points and the low points become shadowed and stop growing. The effect leads to formation a porous film with isolated columns inclined towards the source of the flux [38]. On the contrary, film deposited at lesser angle has greatly increased density due to the lessening of shadowing effect [39].

Although the growth of columns tracks the direction of incoming flux, it was found that the tilt angle β of the columns is remarkably smaller than α [40–42]. A tangent rule between α and β ($\tan \beta = 1/2 \tan \alpha$) was expected [43], but experimental conditions like diffusion length and crystal structure may lead to deviation of this relationship [44,45]. Another phenomenon noted experimentally is that the width of the column increases with the deposition process and the column height, and is attributed to a competitive columnar growth mode [42,46]. In addition, since only the high points can be seen by the deposition flux, it is possible to prepare seeds on the substrate, which can confined the growth of columns to predetermined, regular locations [39]. Researches indicate that the seeds are not required to be perfect with vertical sides but a reasonable aspect ratio is important for the shadowing effect [39]. The size and the cross section of the seed also play trivial roles in the deposition process, but the spacing and the arrangement of the seeds array determine those of the final columns array [39,47].

To prepare the micro-helix or related structures, the substrate should rotate azimuthally at a fixed incident angle α, polarly to change the incident angle. The incident angle α (and corresponding tilt angle β) may also be tuned upon request. Therefore, complex three-dimensional structures can be produced by altering α, substrate rotation behaviors, and deposition rate. For instance, A uniform rotation of the substrate azimuthally was used for helical structure [37,38]. A typical micro-helices array prepared by GLAD is displayed in Fig. 1(c). Rotating the substrate by 180° between successive stationary deposition steps leads to formation of zigzag. A unique tetragonal square helix can even be produced by rotating the substrate stepwise for 90° [6,39].

Many materials can be deposited by this method forming helical structures, but the deposition setup is restricted for those with strong shadowing effect. Evaporation in high vacuum is adopted in most cases [6,47,48], while sputtering may also be engaged in the fabrication [42].

2.4. Rolled-up technique

Rolled-up technique which exploits both bottom-up and top-down methods was invented more than 10 years ago [49,50]. The technique was employed to fabricate three-dimensional structures (typically micro-tubes and micro-helices) by the rolling-up of pre-strained nanomembranes (thin films with thickness < ~100 nm) upon release from an underneath sacrificial layer. The key point here is to introduce a strain gradient perpendicular to the nanomembrane as a driving force of the rolling process. For the multi-layered structure grown by molecular-beam-epitaxy (MBE), this can be conveniently achieved by utilizing lattice mismatch, where the strain/stress is accurately calculated if the layers are coherent [51]. The strain is even tunable in compound semiconductors since the lattice constant varies with the composition. Many kinds of semiconductor nanomembranes have been successfully rolled in the past [52–55]. Besides the expensive epitaxial growth, the non-epitaxial deposition may also introduce strain by intentionally altering the experimental parameters such as vacuum and temperature [56–58]. Another point in this technique is selecting a sacrificial layer with high etching selectivity with respect to active layer in the same etchant and thus the active layer can be kept intact when the underneath sacrificial layer is etched away. This requirement is sometimes not so easy to reach especially for the semiconductor multi-layers. In 2008, a modified rolled-up technique was reported which engage an organic sacrificial layer [51,58]. Then the normal organic solvents (e.g. acetone and ethanol) are able to etch the sacrificial layer over almost any inorganic active material with practically 100% selectivity. Therefore, limitations on materials selections are largely exempted and nanomembranes constructed from a range of inorganic materials and their combinations can in principle be rolled [51,52,58]. The use of the organic photoresist as the sacrificial layer also provides the convenience in accurately positioning the rolled microstructures [51], which is beneficial to future device fabrication. To date, the rolled-up technique demonstrated good controllability and tunability, and as a versatile method, it has been widely engaged in microstructure fabrications.

The diameter of rolled-up micro-structure is decided by the strain gradient and the stiffness of the nanomembrane, while the geometry of the resulting structure mainly depends on the rolling direction and the shape of the nanomembrane. The anisotropy in the stiffness remarkably influences the geometry because the nanomembranes prefer to roll along the compliant direction due to the elastic energy minimization [59]. In single crystal SiGe/Si or InGaAs/GaAs multi-layer, the <100> directions are the most compliant with the smallest Young's modulus, and the rolling along this direction is energetically favorable [49,60–63]. If the nanomembrane is patterned into a stripe with orientation at some angle relative to the compliant direction, rolling will lead to formation of a helix [59,64–67]. Fig. 1(d) shows a typical micro-helix made from SiGe/Si/Cr multi-layered nanomembrane [63]. Detailed characterization disclosed that in SiGe/Si system, the angle between the stripe's orientation and the closest <100> direction decides the chirality and helical angle of the resulting helix [59,64]. One may also deduce that the helical angle mush larger than 45° due to the symmetry in crystal lattice [64,65], however, this restriction has later found to be overridden in very narrow stripe [65]. The edge effect therein causes partial strain relaxation at the sides, producing a uniaxial strain component along the stripe. In such circumstance, helices with helical angle less than 45° can be obtained [65]. Researcher also notices an additional isotropically strained Cr layer on the top of SiGe/Si/Cr stripe can take the same effect, especially in stripe with narrow width and thick Cr layer [42].

The nanomembrane deposited by other techniques like evaporation and sputtering normally possess poly-crystal or amorphous nature, and therefore is usually elastically isotropic [68]. There is no preferential rolling direction and fabrication of micro-helix seems challenging. We recently developed a feasible methodology for fabrication of micro-helix made from metallic stripe deposited using evaporation [69,70]. The key point here is that the flux of the materials is deposited onto the organic sacrificial layer with an oblique angle, which is so-called oblique angle deposition (OAD). Experimental observation proves that the rolling direction is exclusively dominated by the incident direction during deposition, i.e. the rolling direction is always vertical to the incident direction [69,70]. The existence of the anisotropy in this metallic nanomembrane should originate from the structural asymmetry produced by OAD [38,42]. Since the nanomembrane deposited is multi-crystal or amorphous and exempted from the lattice symmetry as in single-crystal nanomembrane, there is only one preferential direction. The limitation in helical angle no longer exists and thus we can produce micro-helices with helical angle in the range from 0° to 90° [69].

The research carried out in our group recently found that it is possible to increase the anisotropy in the metallic nanomembrane by creating some fine structures (Fig. 1(e)) [71]. As schematically shown in Fig. 2(a), a 200 nm thin layer of PMMA (Poly(methyl methacrylate)) was spin-coated on the substrate and then subjected to nanoimprinting with Si grating mold. After de-molding, the grating structure was transferred from the mold to the PMMA layer (see also Fig. 2(b)). Metallic Ti nanomembranes were deposited onto the patterned PMMA layer by e-beam evaporation and rolled into micro-helix after removal of the sacrificial PMMA layer. The grating structure was found to be transferred to micro-helix's wall, as shown in Fig. 2(c) and (d). We found that the rolling kinetically favors the direction perpendicular to the gratings, which is accordingly defined as the preferential rolling direction [71]. On the basis of this finding, we have designed stripes with misaligned angles increasing from 7° to 47° in a step of 10° relative to the gratings as illustrated in the upper panel of Fig. 3(a). The fabricated micro-helices after removing the sacrificial layer are presented in Fig. 3(b), and the image evidently shows grating-structured micro-helices marked from ‘1’ to ‘5’ with a helical angles of 83°, 73°, 63°, 53°, and 43°, respectively. This work demonstrates that anisotropy can be controllably introduced by modifying the topology of the nanomembrane before rolling, which then provides convenience in tuning the helical angles and the chirality of the micro-helices [71]. Besides, since this approach employs top-down method, array of micro-helices can thus easily be fabricated as shown in Fig. 1(e).

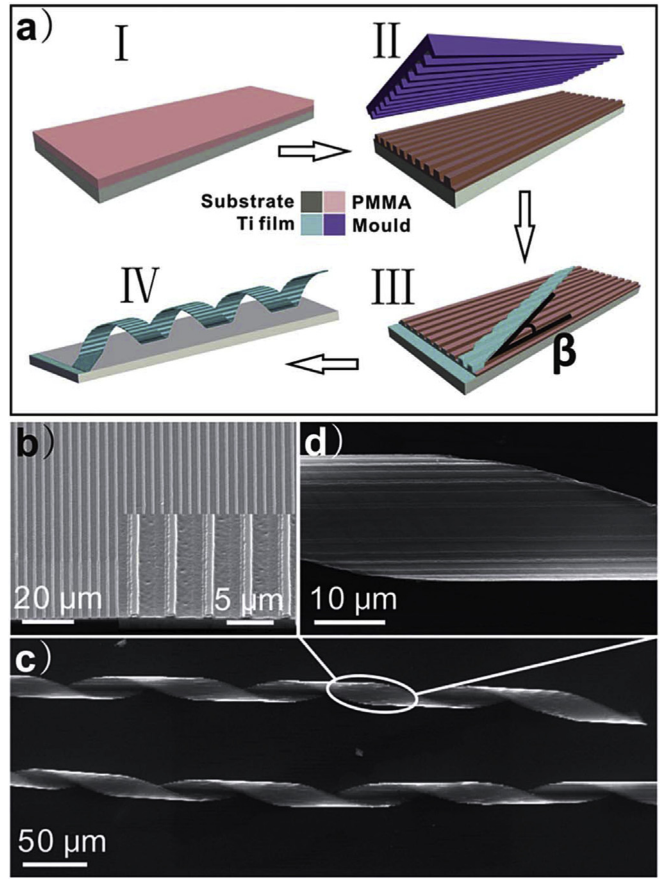

Fig. 2. (a) Process flow of grating-structured micro-helices. (b) SEM image of grating structures on PMMA. The inset shows the magnified image. (c) SEM image of grating-structured micro-helices. (d) Enlarged image of grating structure on micro-helix. Reprinted with permission from Ref. [71].

It is worth noting that an isotropic stripe can actually roll into a micro-helix too [52,56,67,72,73]. In principle, an isotropic stripe will roll into a ring, but if the rolling length is longer than the perimeter length, more rotations will be formed with gradually increasing diameter. The deviation of the larger diameter from the optimal value leads to increased bending energy. If, on the other hand, the stripe forms a micro-helix with all the rotations in the helical structure adopting the optimal radius, the bending energy is minimized but with some cost in shear energy [67]. The final geometry is determined by the total energy. A calculated “phase diagram” based on the geometries and elastic properties of the stripe was present in Ref. [67], which defines the thermodynamic limit for rolled-up micro-tube versus micro-helix formation. But in reality, obtaining a micro-helix from isotropic stripe may be influence by external factors like force applied [67] and lateral etching behavior [74].

2.5. Other approaches

With the development of the micro-/nano-fabrication technique, new methods are always invented to create desired structures. In this paper, we can hardly list all the approaches

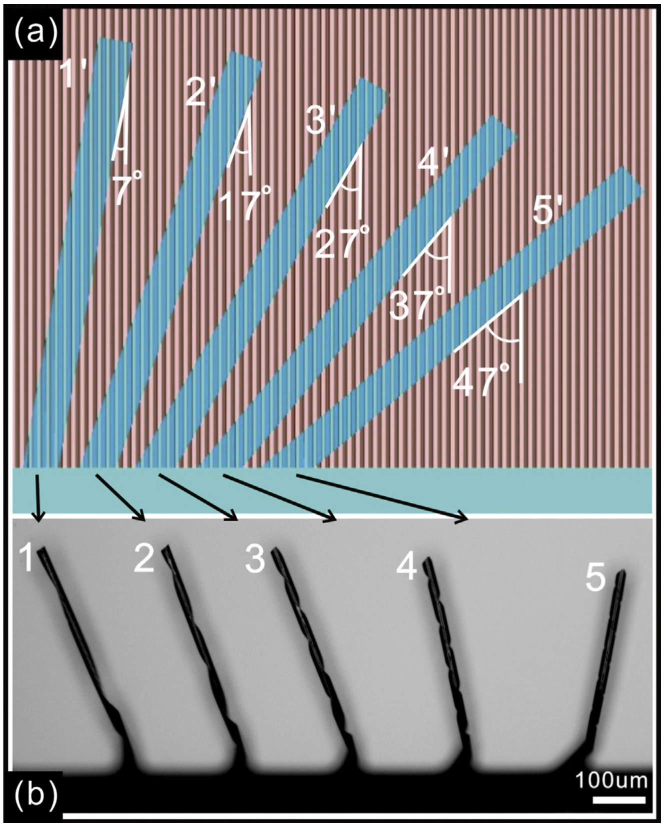

Fig. 3. (a) Schematic diagram of stripes with increasing misaligned angles in a step of 10°. (b) Corresponding optical image of micro-helices with helical angles of 83° (1), 73° (2), 63° (3), 53° (4), and 43° (5). Reprinted with permission from Ref. [71].

and therefore we only briefly introduce a few typical methods of producing micro-helices.

2.5.1. Photolithography-etching

The standard photolithography-etching process is widely used in integrated circuits with the ability to prepare two-dimensional structures determined by the photolithography masks. A two-dimensional micro-spiral structure was easily fabricated by this means, and the structure is transferred into a conical helix under the external electrical field. The pitch of the helix is found tunable under different magnitudes of the electrical field [75].

2.5.2. Twist-spinning

CNT yarn made by twist spinning process has stimulated tremendous interest [76−79]. The process normally stopped when a CNT sheet (produced by CVD, for instance) was spun into a yarn [76,77]. A slight over-twisting of the yarn was recently found to cause the formation of a helical structure consisting of self-assembled loops [78].

2.5.3. Electro-spinning

Electro-spinning uses an electrical field to draw very fine fibers from a liquid. Researchers have produced helical poly styrene fibers by using a direct electro-spinning method where flowing water was engaged as the collector surface [80,81]. The diameter of the fiber is influenced by the liquid concentration while the pitch length of the helix is mainly determined by the electrical field applied [81].

3. Properties and applications

As we know, micro-helices have been fabricated from various materials by different approaches. Their properties and applications were also extensively investigated in the literature. In this section, we will classify and summarize the important properties of the micro-helices and their applications will also be demonstrated, especially in mechanics.

3.1. Mechanics

The most important application of macro-scale helix is being used as a spring, and therefore the mechanic properties of micro-helices are the focus of many researches. Due to the small dimensions of the structure, the studies may carry out with the help of microscopy, and the stretching process is accomplished by a cantilever or micro-manipulator [26,47,59,82]. By this means, the relationship between the elongation and the force applied was easily probed and the corresponding spring constant can be calculated. The mechanical properties depend on not only the nature of the material that the helix made from but also the geometrical parameters. Theoretical researches present detailed dependence of mechanical properties on geometries [26,59,82], and therefore, micro-helix with the required stiffness can be designed by choosing suitable parameters such as the number of turns, thickness, diameter, or pitch length [59]. In rolled-up micro-helices, since the driving force originates from the internal strain, the geometry of the micro-helices can thus be tuned if the strain is varied. The volume expansion of polymers in different chemicals was found to change the rotations of polymer/metal micro-helices (see Fig. 4), which indicates the possibility of using such kind of micro-helices as chemical sensors [69,70]. It is worth noting that helices in micro-scale were found to possess superelasticity. That is, the micro-helix can be repeatedly stretched to an almost straightened shape and recover its original state after releasing with no damage [22,26,69,78]. The excellent mechanical properties of the micro-helices compared with their counterpart in macro-scale are considered to be due to the small dimensions [26], which suggests potential application as flowing rate sensor (see Fig. 5). Micro-helices in the liquid extend longer in response to the increase of the liquid flowing rate [69,71]. The relationships between the flowing rate and the elongation for four typical micro-helices are plotted by using different symbols in Fig. 5 and the solid curves are from theoretical calculation engaging geometry parameters of the micro-helices, and a good fit is noticeable [71]. Detailed theoretical calculation can be found in Refs. [69] and [71].

The excellent mechanical properties of micro-helices also guarantee their applications in elastic energy storage, buffer, etc [22,79]. For instance, a clock can utilize the potential

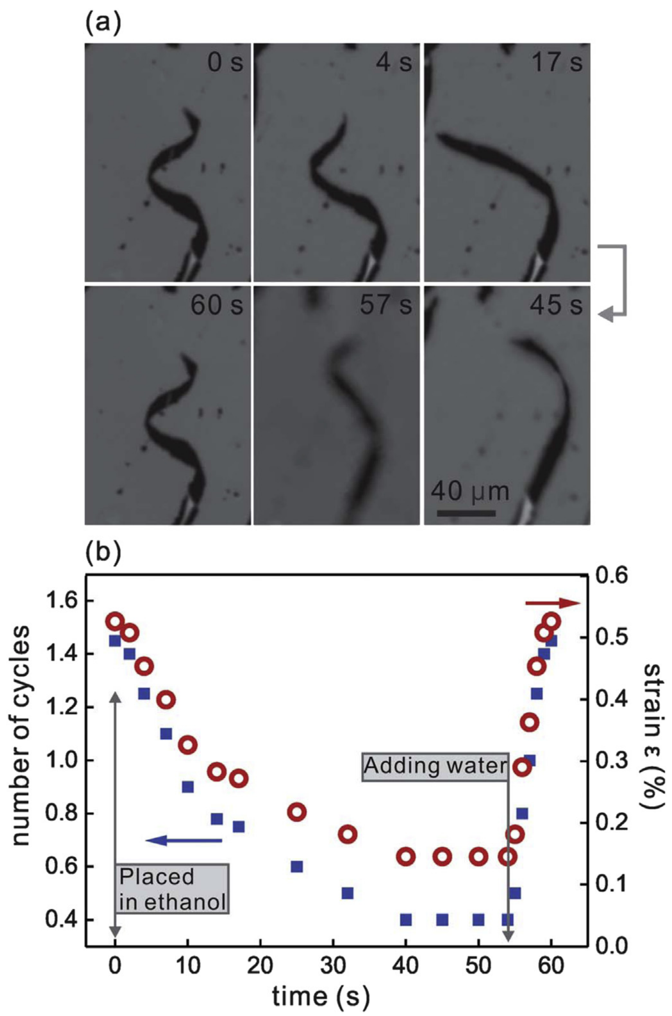

Fig. 4. (a) Time profiles of unrolling and rolling motions of a metal/polymer micro-helix in different solvents. The micro-helix was placed into pure ethanol at 0 s, and water (the volume ratio of water to ethanol was 1:10) was added into the solution at 54 s. (b) Time-dependent number of cycles in a Cr/PVA–PAA micro-helix and the strain during the process. Reprinted with permission from Ref. [70].

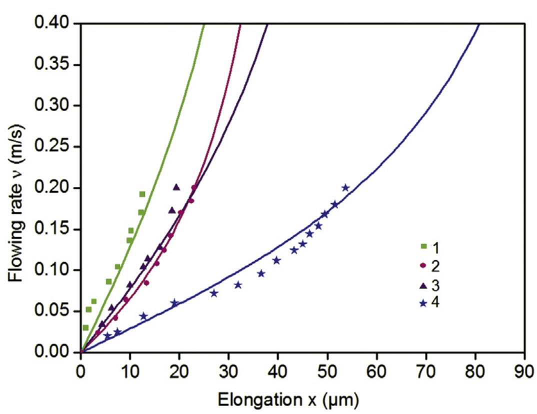

Fig. 5. Flowing rate (v) vs. elongation (x) (solid curves) based on theoretical calculation fits the experimental results for four different micro-helices. Adapted with permission from Ref. [71].

energy stored in a wound micro-helix to turn gears, as shown in Fig. 6(a) [83]. Micro-helices are also used in a recently developed display technology named Interferometric modulator display (IMOD, trademarked Mirasol). Each IMOD element is a MEMS-based device where an air gap can be tuned with the help of a micro-helix. An element thus behaves like a tunable optically resonator whose reflected color is determined by the size of the air gap, as schematically illustrated in Fig. 6(b) [84].

As mentioned before, the helix can couple rotation and translation movements due to its unique geometry. In the micro-world, this is a very useful strategy for propulsion in low Reynolds number regime [85]. For instance, *Escherichia coli* bacteria use their helical flagella to generate a corkscrew-like motion [86]. Inspired by this locomotion in nature, researchers developed micro-swimmers from micro-helices

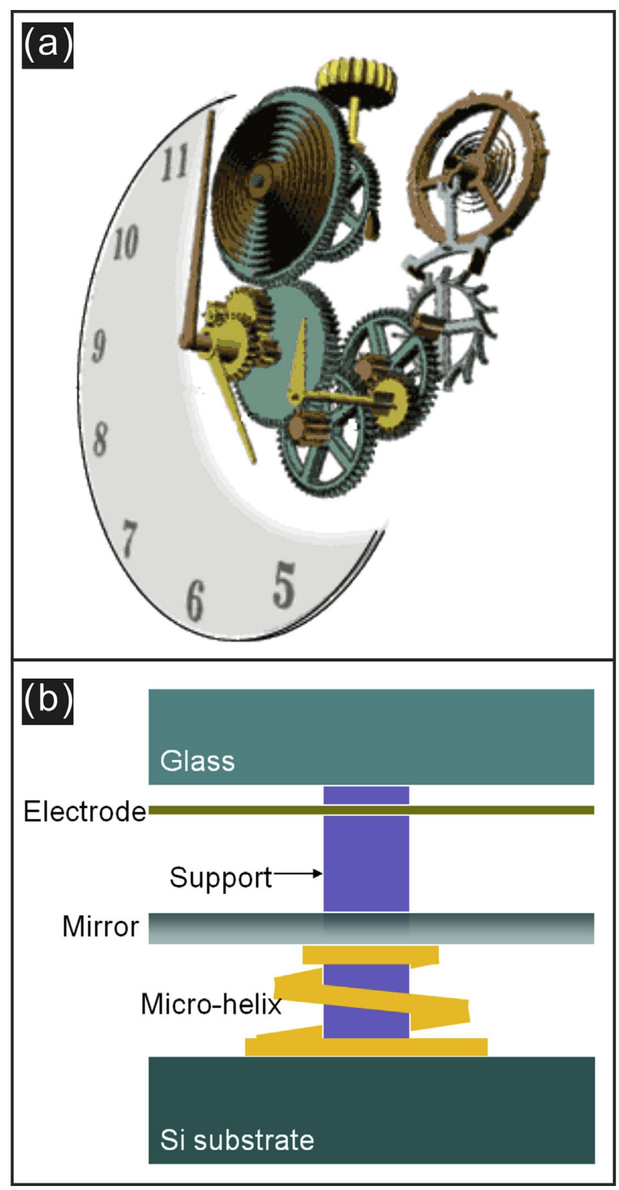

Fig. 6. (a) clock utilizes the potential energy stored in a wound micro-helix to turn gears [83]. (b) Illustration demonstrating the principle of the IMOD [84].

[30,48,87,88]. The micro-helices performing this task normally consist at least partly of a magnetic material, and therefore can be remotely and wirelessly controlled by an external magnetic field. In the case of rotating magnetic field, the torque generated forces the micro-helix rotated along its helical axis and self-propelled like a screw [48,87]. The velocity of the micro-swimmer is revealed to be a function of both magnetic field strength and rotation frequency [88]. As shown in Fig. 7, the velocity increasing linearly with the increasing frequency, but after reaching a maximum value, the velocity reduces because the magnetic field is no longer sufficient to keep the swimmer rotating synchronically [87,88]. By exerting a stronger magnetic field, a larger maximum velocity can be achieved at a higher rotation frequency [87,88]. On the other hand, the direction of the locomotion was reported to be precisely steered by using three orthogonal electromagnetic coil pairs, and complex tasks can therefore be accomplished [88]. Since the helical micro-swimmers have important potential for in vitro and in vivo biomedical applications, theorists recently give the clue on future geometrical optimization for micro-swimmer with improved performance [89].

3.2. Electrics

The conductivity of a micro-helix is determined by the material composing the helix. A micro-helix made of conductor or semiconductor is capable of conducting current if a potential is applied to the two ends [33,47,63,78,90]. The additional benefit is that the total resistance is relatively stable if the helix is stretched, because the loop opening significantly reduces the strain in the materials [78]. Nevertheless, the effect from the strain was still noticeable in certain semiconductor materials. Hwang et al. [62] measured the current–voltage curves of the micro-helix with different elongations, and found an increase of current with larger elongation, due to complex strain evolution in the GaAs. When the helix is elongated, the changes in electron effective mass, carrier mobility, electron trap, as well as piezoelectric charges induced by stress gradients may lead to changes in the resistivity and cannot be described by a simple model [62]. This piezoresistive response of the helix suggests its potential application as electromechanical sensor.

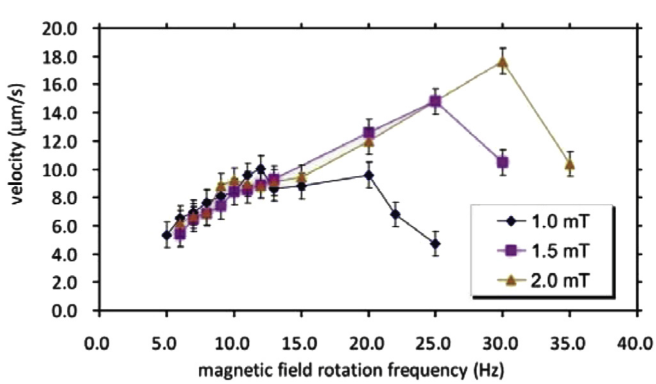

Fig. 7. Dependence of velocity on strength and rotation frequency of the applied magnetic field. Reprinted with permission from Ref. [88]. Copyright 2009 American Chemical Society.

Besides the individual micro-helix, the electrical properties of an array of densely packed micro-helices were also studied [42]. The helices array actually forms a porous structure, and the open gap between the helices leads to a higher resistivity compared to the original bulk material. Under a compressive load, the helices will touch their neighbors, providing a path for current to flow between the helices and consequently reducing the resistance. The >50% change in resistance upon loading and unloading make the micro-helices array suitable for pressure sensing [42].

3.3. Magnetics

The magnetic properties of the micro-helices have been investigated in two ways. First, the micro-helix can be made from magnetic materials, and in this case, the aforementioned rolled-up technique provides great convenience in controlling the magnetization orientations [52]. By rolling stripes with different magnetization orientations (e.g. out-of-plane and in-plane orientation), micro-helices that are radial-, corkscrew-, and hollow-bar-magnetized were fabricated, and the continuously distributed macroscopic magnetic moment of the micro-helices resembles that of the discrete spin patterns of helimagnetic materials [52]. Due to different magnetization configurations, the magnetic micro-helices will response to external magnetic field differently and can be easily visualized by recording their motion trajectories. Both experimental and theoretical works have been carried out to disclose this interaction in detail [52,91].

Second, it was found that a conduction micro-helix with current flowing through may be regarded as a solenoid [33]. For instance, a Ag micro-helix demonstrated self-inductance at the picohenry was reported and the measured magnetic moment is linearly dependant on the current [33]. A sophisticated experiment performed by using microscopy show that the micro-helix with current passing can be electromechanically actuated: the electromagnetic force leads to compression of the helix [33], implying its future applications in MEMS.

3.4. Optics

Due to the unique three-dimensional geometry, the micro-helices show interesting optical properties when their feature sizes are comparable to the light wavelength. The potential applications of micro-helices in the fields of meta-materials and photonic crystals attract increasing interest during the past years [39,92,93], and the interactions between the light and the micro-helices have been intensively investigated.

The micro-helix has the ability to rotate the polarization of the light [38]. When a linearly polarized light is incident on a film consisting micro-helices along the helical axis, the transmitted light shows polarization rotation which is a function of light wavelength [38]. If the incident light possesses circular polarization, the situation becomes complex because the inherent chirality of the helical structure needs to be taken into consideration. Both theoretical and experimental works show that for propagation along the helical axis, the micro-helices will block the circular polarization with the same handedness as the helices, and therefore could be used as circular polarizer or analyzer [28,34,94]. Quantitative analyses demonstrate that the transmittance is influenced by the geometrical parameters like helix diameter, pitch length, and pitch number, suggesting the performance of this kind of polarizers could be improved with structural optimization [94,95]. As a step further, researchers designed and prepared so-called "bi-chiral" structures where the transmittances of both left-handed and right-handed circularly polarized lights should be equal [29,96]. The micro-helix's ability of controlling the polarization will definitely lead to applications as important optical components.

4. Conclusion and outlook

In this review, researches related to micro-helices are summarized. The micro-helices of various materials can be produced by numerous approaches, either "top-down" or "bottom-up". Due to different underneath mechanisms engaged, each method has its own advantages but limitations may also exist. Researchers can choose a best one suitable for his requirements from a number of approaches. The unique three-dimensional structures were found to possess many interesting properties originated from the materials and/or the geometries. Besides the outstanding mechanical properties suggesting their application like a spring, similar to their macro-counterpart, the properties in various disciplines provide great application potentials in e.g. optical components, electronics, mechanical sensors, flat panel display, as well as MEMS/NEMS.

As a rapidly developing field, it is not possible to include all the literature here. We focus mainly on new and important results recently published, and hope to prove a handy reference to the researchers in the field, and meanwhile to stimulate more studies related to micro-helices.

The future of micro-helices lies in many aspects of fundamental science, engineering, and application. Although we have summarized many fabrication techniques in this review, we believe that due to the technological innovations in the future the fabrication can be further expanded both in terms of materials and methodology. New technology may provide more convenient control on geometries of the micro-helices like diameters, helical angles, and chiralities. The helices with the feature sizes from molecular level to sub-macro may be fabricated by using a general strategy and the gaps between nano, micro, and macro can be perfectly filled. In the extremely small scale (i.e., molecular level), the unique geometry of helix will certainly affects its physical or even chemical properties and the underneath mechanism should be investigated in the future. Considering the optimized fabrication and the expected unique properties, we hope researchers can explore more amazing application potentials in electronics, mechanics, fluidics, biology, and photonics. Especially, the applications as sensors and/or actuators may be advantageous for developing smart micro-/nano-robots, because the micro-/nano-helices passively actuate in response to environmental changes like temperature, humidity, salinity, and pH. The tuning of their dimensions makes them perfect building blocks of a large integrative MEMS or NEMS for fascinating on-chip applications.

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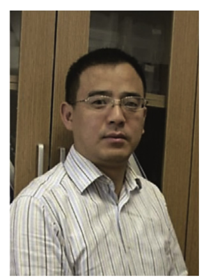

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