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Gold Nanosprings Formed by Rolled-up Technique

Wenting Zhao[a], Pintu Ghosh[a], Jinsheng Lu[a], Ziyao Chen[a], Qiang Li*[a]
[a]State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China

ABSTRACT

Three-dimensional helical nanostructures have attracted a great deal of attention by the virtue of anomalous properties in mechanics, electricity, electromagnetism and optics due to their intriguing shapes. This paper mainly introduces the fabrication of novel gold nanosprings by using the rolled-up technique and studies their mechanical and piezoresistive properties. Cutting across 80 nm thick gold film deposited on silicon substrate with defective nanofiber probes, we fabricate nanosprings with variable size. Maximum elastic elongation and electromechanical resonance of one gold nanospring are measured. Furthermore, we survey its piezoresistive property. It can be inferred that low stiffness, large displacement and strong piezoresistive effect of gold nanospring make it an excellent candidate for potential application as micro electro-mechanical sensor.

Keywords: rolled-up nanofabrication technique, gold nanospring, elasticity, electromechanical resonance, piezoresistivity, nanowelding

1. INTRODUCTION

1.1 Brief introduction to nanospring

Due to a wide range of possible applications and new physical phenomena, the development of nanotubes and nanowire structures have influenced the field of nanoscience greatly. The various electrical, optical, and mechanical properties provided by nanostructures can be used to develop new technology applications.[1] Among these nanostructures, especially spiral nanosprings or nanocoils have special mechanical properties and are suitable for potential applications in nanoengineering. For example, a nanospring, like a macrospring in shape, can be used as a mechanical device operating in a micro (nano) system, similar to double helix DNA.[2] The quantum confinement effect induced by the helical combination of nanometer size may lead to the abnormal transport behavior of electrons and holes, which contributes to the development of new nanodevices. Furthermore, due to the chirality of the incident light and geometrical parameters (such as diameter and spacing) that are comparable to the wavelength of the light, the handedness involved in nanospring may interact in a different manner with circularly polarized light.[3] It can also realize nano-scale electromagnetic function by sensing magnetic field or flowing current. Therefore, they can be used as component in microelectromechanical and nanoelectromechanical systems, such as magnetic field detection, chemical or biosensors, electromagnets, inductors and high-performance electromagnetic wave absorbers.[4]

1.2 Previous studies on fabrication of nanospring

Nanosprings have been observed since 1955, but until recently they were used as potentially useful tools in research. Like other nanostructures, nanosprings are a very simple structure on the nanometer scale but have significant material properties on a macroscopic scale. They are typically grown by a chemical vapor deposition (CVD) process using a vapor liquid solids (VLS) process.[5]Like other nanostructures, they have a very large surface area of up to 400 m^2/g. However, unlike other nanostructures, they also have very low resistance to flowing liquids or gases. The mechanical properties of macroscopic springs are also converted to nanoscale. Schilke was able to use the atomic force microscope cantilever to pull the spring apart, observing that there is no deformation inside the spring, even if it is extended to 50% of its static length.[6] Therefore, the maximum operating temperature at which they can be exposed is determined by the melting point of the material from which they are made of. With the continuous advancement of material chemistry, it is expected that the nano-scale geometry can be precisely controlled soon, so the nanospring with the adjustment geometry will meet the design requirements of different equipment configurations according to the target application.[1]

*qiangli@zju.edu.cn; phone (86)0571-87951628; ipnp.zju.edu.cn

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1.3 Rolled-up nanotechnology and our work in this paper

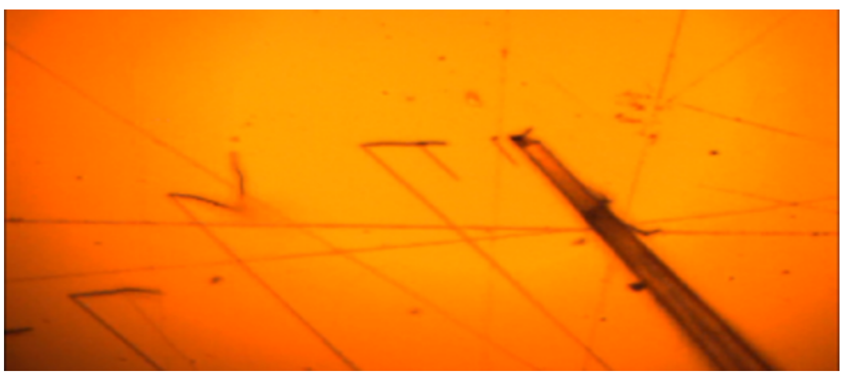
In the past decade, rolled-up nanotechnology has often been used to make new three-dimensional nano structures. In 2000, Russia's Y Prinz et al. first proposed a new method of rolled-up nanotechnology for the preparation of three-dimensional micro-nanostructures.[7] The basic idea of this technology is to detach a two-dimensional film with internal stress from the substrate by etching and it will curl into a three-dimensional nanostructure, such as a tubular structure or a spiral structure.[9] This tubular and spiral nanostructure based on the rolled-up nanotechnology combines the special three-dimensional geometry and the excellent properties of the nano-film material itself, making the research work of the crimped nano-roll technology on modern materials science and microelectronics. Major influences in the fields of science, optics, and biology, including targeted delivery and Micro-/Nano-Electro Mechanical Systems (M/NEMS) A series of new cross-disciplinary disciplines are particularly prominent.[10] In this paper, a new simple way of fabricating 3D helical nanostructures has been presented. We achieve nanometer-scale control of the shape of helix nanostructures through the control of the direction, velocity and depth of the movement of nanofiber probe on 80nm thick gold film coated on silicon layer as Figure 1 illustrates. What's more, with respect to the application in MEMS (micro electro mechanical system), the mechanical and piezoresistive characterization of gold nanospring is done with robotic manipulation and nanowelding technology.

2. FABRICATION PROCESS AND RESULTS

2.1 Fabrication process

As is illustrated in Figure 1, we make gold nanosprings by rolled-up nanotechnology by cutting across 80 nm thick gold film deposited on silicon substrate with defective nanofiber probes. We produce gold helical nanosprings of varying size and handedness orientation through adjusting the cutting direction, depth, and velocity of the nanofiber.

(a)



(b)

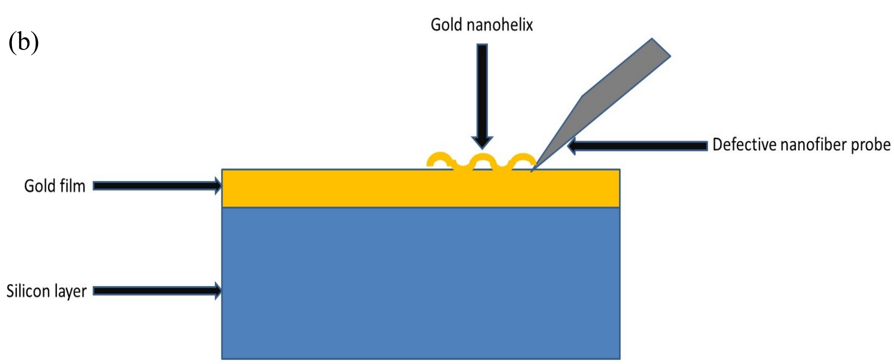


Figure 1.(a) Fabrication process of gold nanospring by cutting across 80 nm thick gold film deposited on silicon substrate. (b) Schematic diagram showing the fabrication process.

2.2 Fabrication results

Using our fabrication technique, structural parameters of helical nanosprings can be tuned in a very wide range, as is demonstrated in Figure 2. Although different sizes and morphologies are achieved, there is one thing worth noting that most of the nanosprings are right-handed, of which the reasons are still unknown.

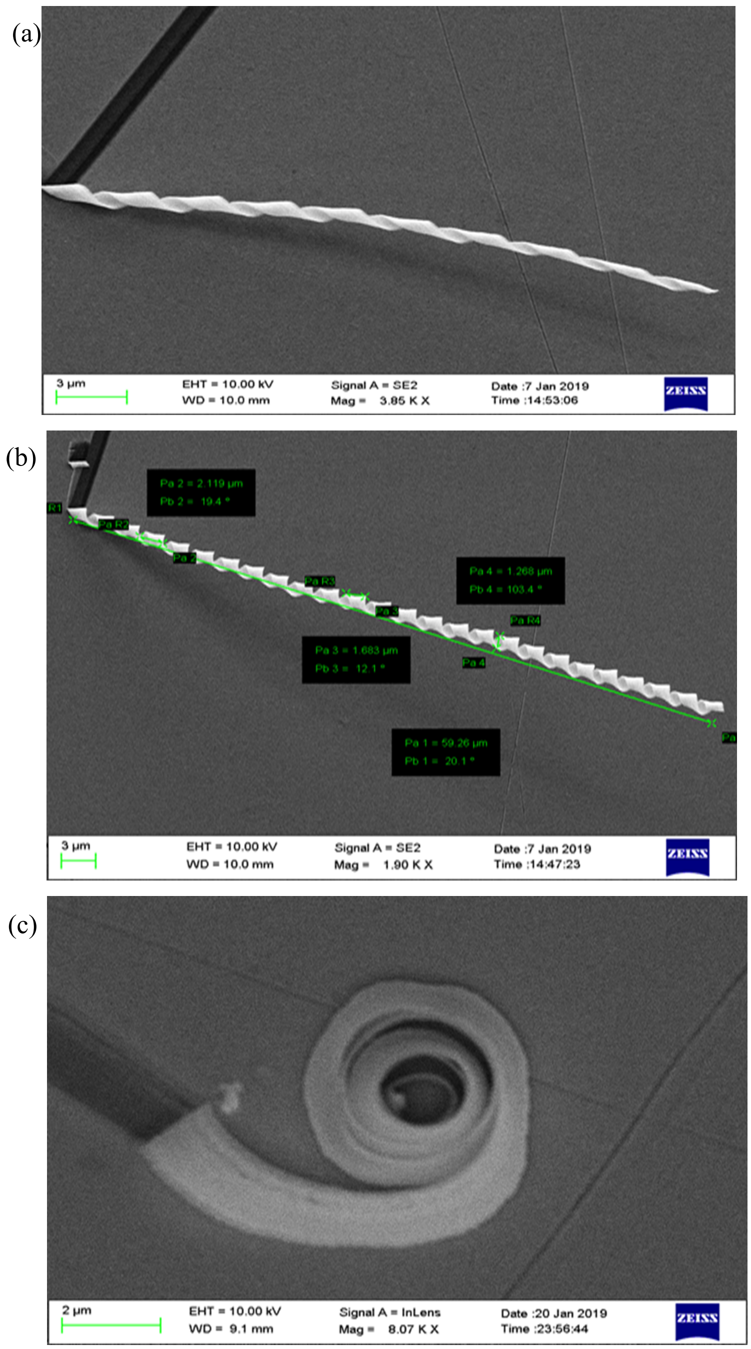


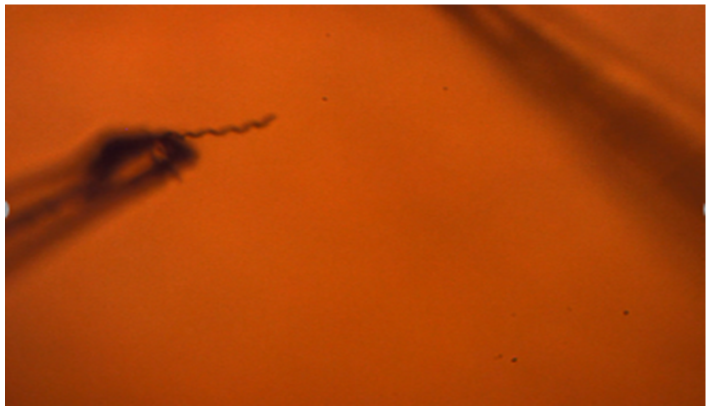
Figure2. Scanning electron microscopy of right-handed gold nanosprings on gold film. (a-c) Gold helix nanostructures with different shapes and sizes.

3. MECHANICAL CHARECTERIZATION EXPERIMENTS

3.1 The elastic tension experiment

For the mechanical characterization experiments, two kinds of nanomanipulators (nanofiber probe and tungsten tipped probe) connected with 3D positioning stage are used. Experiment procedures are displayed. After picking up one nanospring on one side with a nanofiber probe, we use another nanofiber probe to contact the other side of the nanospring.

(a)



(b)

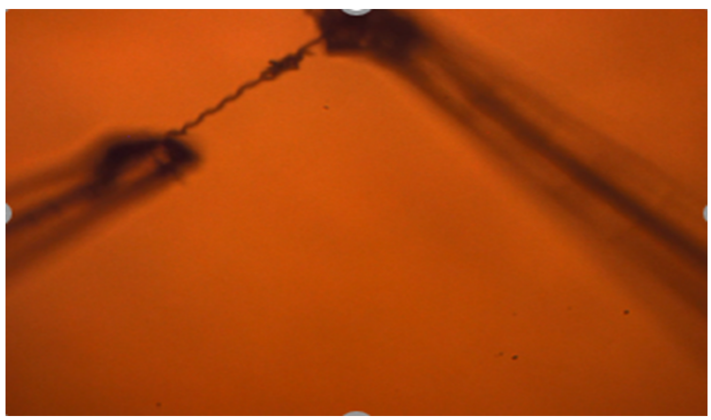


Figure 3. (a)Nanospring at natural state before stretch. (b)Nanospring at ultimate elastic tensile state. The largest elastic relative elongation of the nanospring is 60%.

In order to achieve compact contact with the other side of nanospring, the probe has been dipped in droplet of epoxy already.[7]

3.2 Electrostatic deflection and electromechanical resonance experiment

Furthermore, we apply a time-dependent voltage to the nanospring ($V(t)=V_d\cos(\omega t)$) with a signal generator, which results in a time-dependent force and dynamic deflections of the nanospring. By means of adjusting angular frequency $\omega= 2\pi v$, the resonant frequency can be found when the nanospring is resonantly excited.[8] First we acquire the rough range of the fundamental natural frequency of the nanospring through finite element simulation in COMSOL, which is illustrated.

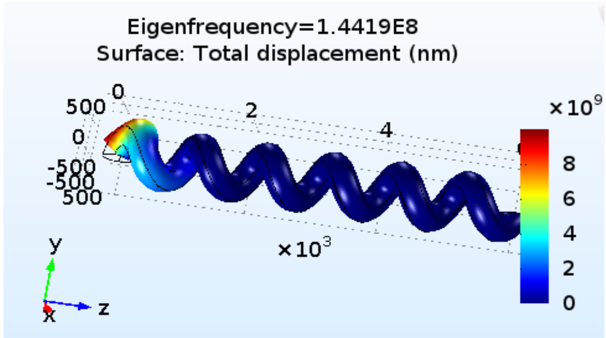


Figure 4. COMSOL finite element simulation of the natural frequency of one nanospring with the same structural parameters with that used in experiment.

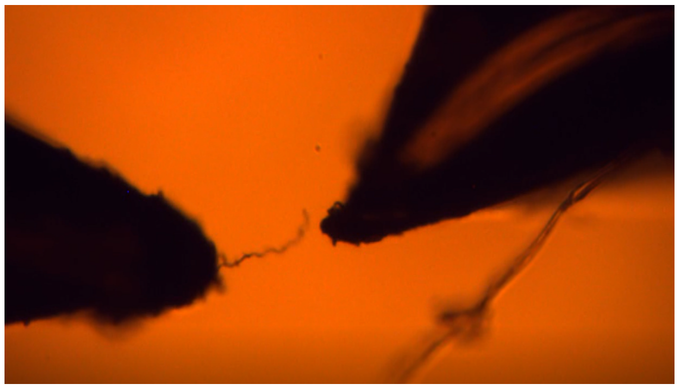


Figure 5. Nanospring under bending resonance caused by time-dependent voltage, of which the frequency is 16.6 KHz.

4. PIEZORESISTIVE CHARACTERIZATION EXPERIMENT

For the characterization of piezoresistance of the nanospring, we measure the current under the same voltage when applied to tensile and deformation pressure. We use nanowelding technology with a continuous-wave (CW) laser beam whose wavelength is 532 nm. [8]

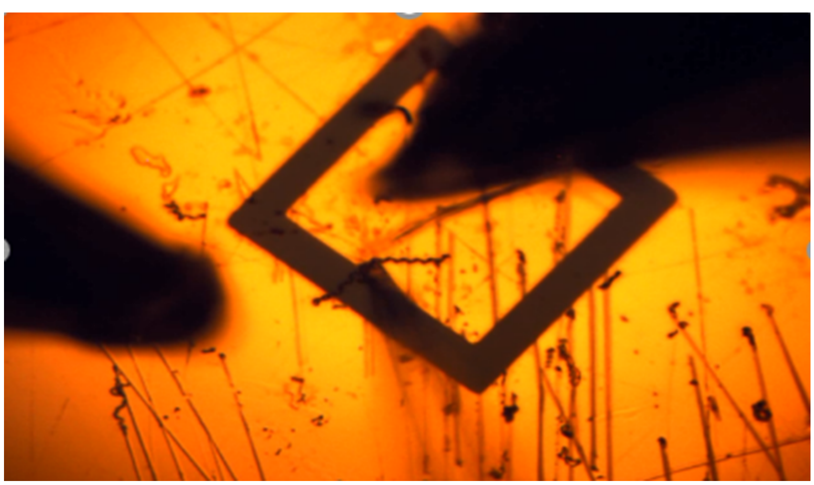


Figure 6. One gold nanospring welded between two gold electrodes is elongated with a nanofiber probe and its electric characteristic curve is measured by two tungsten probes.

5. CONCLUSIONS

In conclusion, the fabricated nanosprings with low stiffness, large displacement, excellent mechanical fatigue resistance and highly-sensitive piezoresistive effect can potentially be used as nanoelectromechanical sensor. Furthermore, our fabrication technique is readily extendable to other materials, which may open new avenues for its application. What's more, in this paper, we use metal crimp nanostructures for electromechanical sensing. However, there are still many other applications for such new microstructures to be discovered. For example, combined with the super-elastic properties of metal nanosprings, it can be used for energy storage; using the spiral structure of metal nanosprings as a miniature inductor, its application in the field of nano-electromechanical systems can be realized.

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