Focused-Ion-Beam Introduced Bidirectional Bending for Complex Three-Dimensional Structures

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This paper reports for the first time the phenomenon that aluminum cantilever in several hundred nanometer thickness can be controlled to bend downward or upward under Ga+ focused-ion-beam (FIB) irradiation. The phenomenon is employed as an approach to assemble complex three-dimensional (3D) micro/nano-scale structures including helixes with different chiralities, clockwork springs, “tubes”, serrate structures, and wave-like structures, etc. The achieved structures have broad applications, e.g., left-hand and right-hand helixes can work together as a micro/nano electrical transformer.

Previously, some structures were reported to be deformed under FIB irradiation, including Si_3N_4 cantilever, [1] silicon nanowire, [2] nano-cabon-pillar, [3] and carbon nanotube. [4] Those experiments are limited to only upward bending, and high dose of incident ion is needed, which induces excessive sputtering of the target materials as well as too much ion implantation resulting in heavy surface damage. These will negatively affect the mechanical and electrical properties of the obtained structures. In this paper, we report that the bending direction can be controlled both downward and upward, in which the downward bending causes less damage.

The aluminum cantilevers were irradiated by FIB near their fixed-ends. They are observed to bend first downwards and then upwards with the increase of FIB irradiation (Fig.1). Fig.2 summaries the cantilever bending-angle variation depending on the ion dose and energy, which reveals that there exists a threshold dose of bending change from downwards to upwards under certain ion energy. The phenomena indicate the balancing process between compressive and tensile stress introducing. In addition, the minimum curvature radius of 250nm is achieved under 25keV ion irradiation, and upward bending will not stop until the bended structures block the irradiation.

Based on the phenomena, helixes (Fig.3(a)) were fabricated by sequential FIB irradiation of same pattern but with different doses to implement different chiralities, diameters and turns. A helix with left-hand chirality part as well as right-hand chirality part (Fig.3(b)) was also fabricated. Notably, the FIB-induced surface material damage in the downward bending is much less than that in the upward bending. Further, a “tube” structure with inner diameter less than 1 μm was formed (Fig.3(c)) Fig.3(d) illustrates two adjacent helixes together forming an electric transformer. Their free-ends were fixed to metal pad via FIB-CVD platinum to achieve electrical connection. Combining the bidirectional bending, a clockwork spring structure (Fig.4(a-d)), serrate (Fig.4(e)) and wave-like (Fig.4(f)) structures have been fabricated. Therefore, the bidirectional bending is an essential improvement for the previous FIB-SIT.

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[2] K. Jun, *et al.*, J. Vac. Sci. Technol. **27**(2009), pp. 3033-3047.

[3] S. K. Tripathi, *et al.*, Nanotechnology **19**(2008), pp. 205302.

[4] B. C. Park, *et al.*, Adv. Mater. **18**(2006), pp. 95-98.

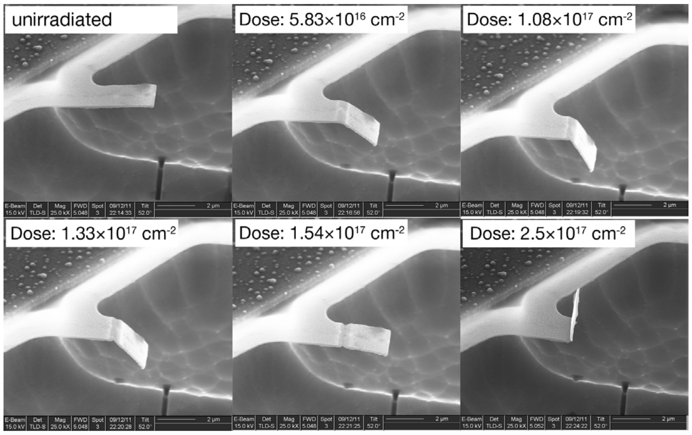


Figure 1: An aluminum cantilever bends from downwards to upwards by localized FIB irradiation near its fixed-end and with dose increase. The irradiation area is 0.25µm wide and 3µm long.

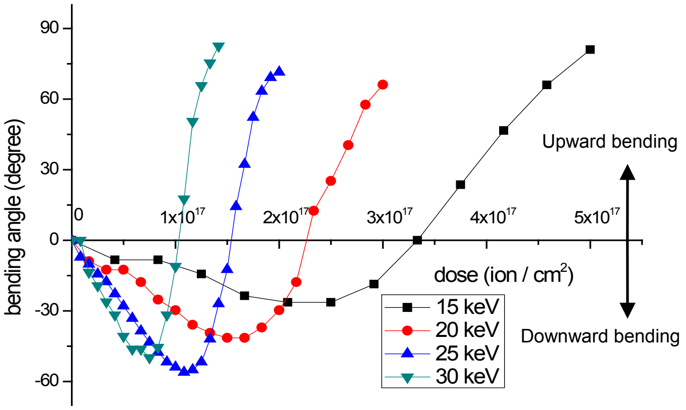


Figure 2: Experiential results of the bending angle under different FIB settings, which indicate that the cantilevers bend first downwards and then upwards with ion dose increase, and larger ion energy causes higher bending speed.

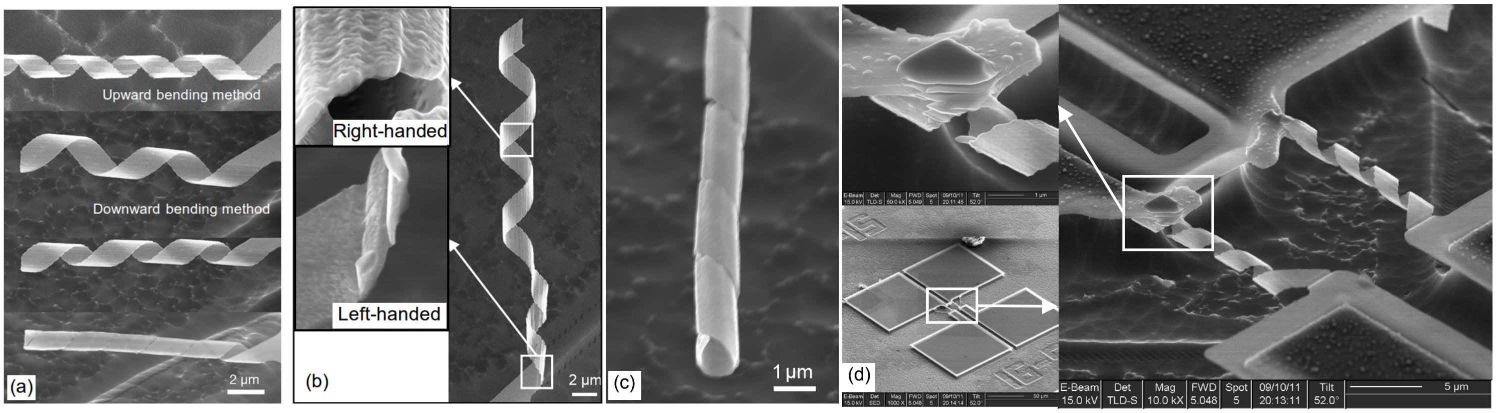
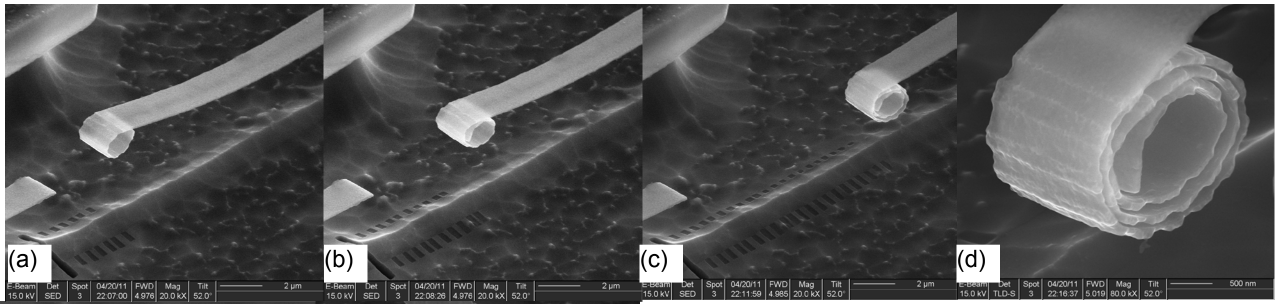


Figure 3: (a) One right-handed helix (top) made by upward bending and three left-hand helixes (the others) with different diameters and turns assembled by downward bending. (b) Helix with left-hand chirality part as well as right-hand chirality part was fabricated by combining downward and upward bendings. The magnified SEM image of the helix shows that downward bending method is with less damage. (c) 52 tilt view of the last helix in (a) with the least diameter, which shows that it forms a "tube" with inner diameter less than 1µm. (d) Two helixes are produced together as an electric transformer by downward-directional bending.



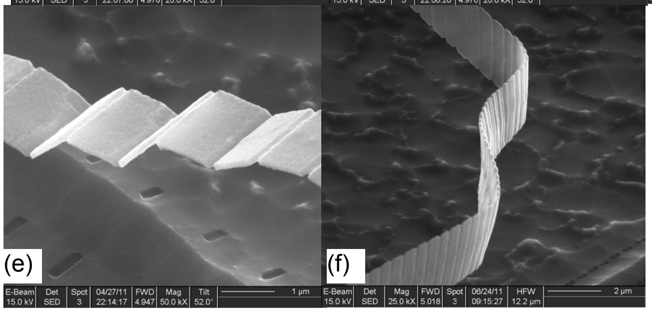


Figure 4: (a-c) Detailed process of fabricating a clockwork spring structure by downward bending; (d) Magnified SEM image of the final structure. (e) Serrate structure and (f) wave-like structure by bi-directional bending.