Supporting Information

Synthesis, growth mechanism and elastic property of SiC@SiO_2 coaxial nanospring

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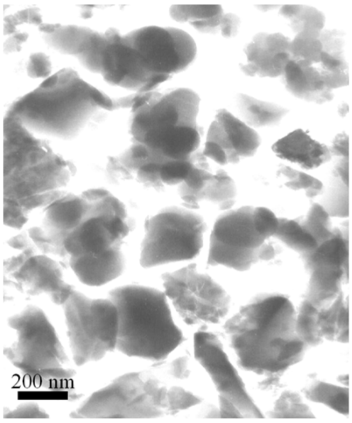

Fig. S1 TEM images of milled Si-SiO_2 mixture powders before reaction

Fig. S1 shows the typical TEM image of the milled Si-SiO_2 mixture powders before reaction. It can be observed that the raw material is irregular particles with sizes range from 120 to 300 nm.

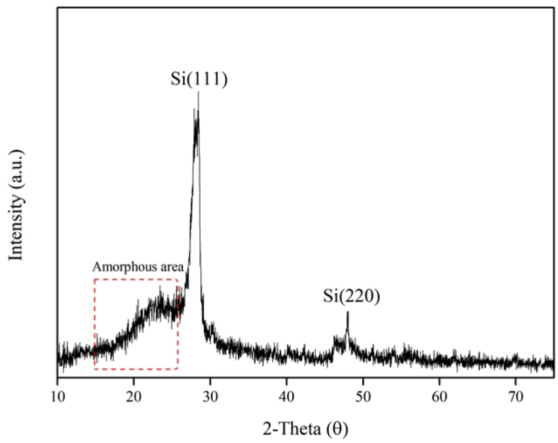

Fig. S2 XRD pattern of milled Si-SiO_2 mixture powders before reaction

Fig. S2 exhibits the XRD pattern of milled Si-SiO_2 mixture powders before reaction. Two obvious diffraction peaks have been detected and indexed to Si (JCPDS Card No. 27-1402) marked as (111) and (220), suggesting that cubic SiC is the only crystalline phase besides the graphite substrate. The broad XRD peak at low diffraction angle (~20°) is aroused by the milled amorphous SiO_2 powders.

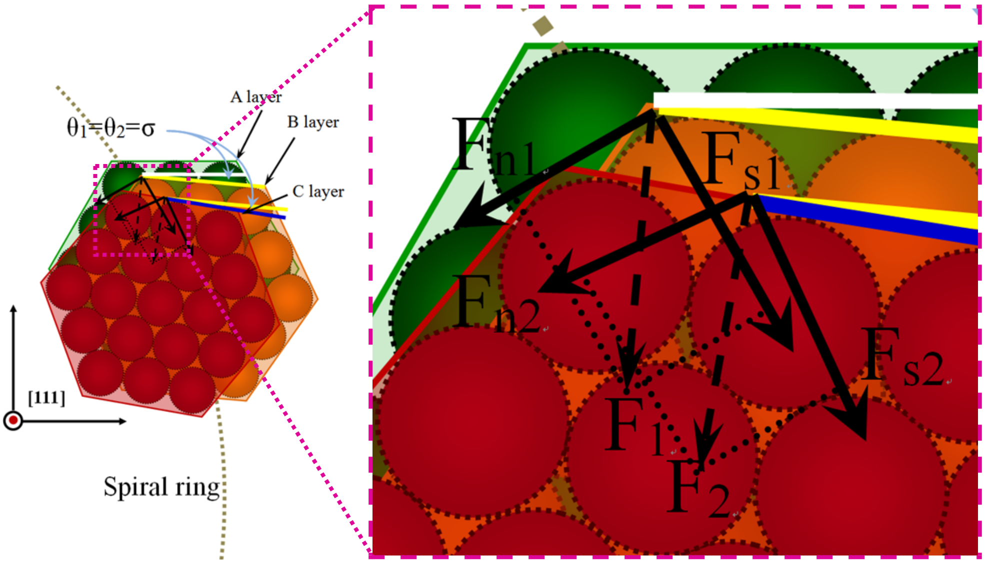

Fig. S3 Force analysis of the radial direction between adjacent atomic layers according to the proposed atomic layer dislocation stacking growth model

As is well known, classical mechanics theory tells us that the helical structure can only be obtained by exerting a constant vertical force upon a body of uniform circular motion. Similarly, the formation of the SiC@SiO_2 coaxial nanospring can also be attributed to the combined effect of radial component force and axial component force.

Firstly, we think that the axial force for growing the SiC@SiO_2 coaxial nanospring can be provided by the nucleation energy during the reaction process. Secondly, according to the proposed growth mechanism in the manuscript (Fig. 4), the radial direction force between adjacent atomic layers is analyzed, as shown in Fig. S3. It can be observed that the distortion energy can generate a stress (F_1 or F_2) between A (or B) layer and B (or C) layer, which is always perpendicular to the tangential direction of the correpsonding distortion atomic layer. We speculate that the stress is a vector connected with the magnitude and direction of the corresponding angular separation θ. The generated stresses can be divided into two parts, the centripetal force (F_{n1} and F_{n2}) and shear force (F_{s1} and F_{s2}). The centripetal force guarantees uniformity of the screw diameter of the single SiC@SiO_2 coaxial nanospring, and the shear forces become driving forces rotated about the center of circle. In other words, the uniform circular motion for growing the SiC@SiO_2 coaxial nanospring can be achieved by the additive effects of the centripetal force and shear force (that is generated stress).

In conclusion, the SiC@SiO_2 coaxial nanospring rather than screw dislocation can be obtained after the end of reaction according to the proposed mechanism. The above explanation demonstrates that the proposed atomic layer dislocation stacking growth model is reasonable on theory.

Although there is no direct method to observe the distortion energy, and the stress can also not be measured directly. As shown in Fig. 3, it can be clearly observed that both the screw diameter of the as-synthesized SiC@SiO_2 coaxial nanospring and the size of every component are changeless. In addition, the stacking direction of the SiC core keeps invariable along the growth direction, which is in accordance with the proposed model. Certainly, further studies and more precise evidences for the growth process of the SiC@SiO_2 coaxial nanospring will be collected in our future works.

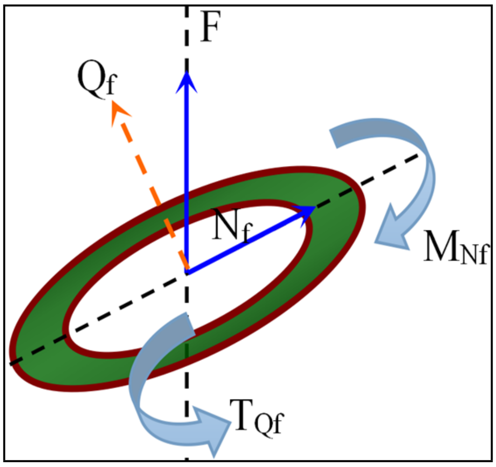

Fig. S4 The repetitive mechanical unit of the nanostructure for the calculation of the spring constant

In order to simplify the model, one geometric symmetry cycle is taken as the repetitive unit of the nanospring for the calculation of the spring constant as shown in Fig. S4, and the corresponding mechanical response can be divided into four terms, shear force Q_f, tension force N_f, bending moment M_{Nf} as well as torsion moment T_{Qf}, when an uniaxial load F is applied upon the nanospring[19, 21].

Assuming that the ends of the nanostructure can rotate freely, and the friction-induced fixation momentum as well as the SiC-SiO_2 interfacial bonding can be disregarded, furthermore, the shear modulus of the coaxial nanospring is constant during the deformation process. The formula of the spring constant (K) can be described by[19,21]:

$$\frac{1}{K} = \frac{H^2}{l_0 EA} + \frac{4\pi^2 \alpha_s r^2}{l_0 GA} + \frac{H^2 r^2}{l_0 EI} + \frac{4\pi^2 r^4}{l_0 GJ} \qquad (1)$$

Where r is the real-time radius of the nanospring, l_0 is the total length of an unit cycle as shown in Fig. S4, which can be seemed as a constant and is equal to the the original nanospring length: $l = l_0 = \sqrt{4\pi^2 r_0^2 + H_0^2}$. The pitch distance H can be illustrated as $H = \sqrt{l^2 - 4\pi^2 r^2}$. α_s is the shear coefficient, which can be given as $\alpha_s = \frac{7+6v}{6(1+v)}$, herein, υ is the Poisson's ratio (constant approximately equal to 0.17 for SiC and SiO_2). Furthermore, the tensile modulus (E) can be derived as a function of υ and shear modulus (G) as $E = 2(1+v)G$. A is the cross-sectional area of the nanospring, herein, which can be regarded as circular for SiC@SiO_2 coaxial nanospring. I is the moment of inertia, and J is the polar moment of inertia of the cross section, the corresponding parameters can be expressed respectively as:

$$A_{SiC} = \pi \frac{d_0^{\ 2}}{4}, \quad I_{SiC} = \frac{\pi d_0^{\ 4}}{64}, \quad J_{SiC} = \frac{\pi d_0^{\ 4}}{32} \tag{2}$$

The above parameters and formula (2) are plugged into the formula (1) as following:

$$K = \frac{G l_0 d_0}{\left[\frac{2l_0^2}{(1+v)\pi d_0} + \left(\frac{8\pi(7+6v)}{3d_0(1+v)} + \frac{32 l_0^2}{(1+v)\pi d_0^{\ 3}} - \frac{8\pi}{(1+v)d_0}\right) r^2 + \left(\frac{128\pi}{d_0^{\ 3}} - \frac{128\pi}{(1+v)d_0^{\ 3}}\right) r^4\right]} \tag{3}$$

The value of shear modulus, Poisson's ratio, diameter of the SiC core nanospring ($G_{SiC} = 192GPa$, $v = 0.17$ and $d_0 = 25\times10^{-9} m$) are plugged into formula (3), and the spring constant of SiC core nanospring (K_{SiC}) can be expressed as a function of the radius:

$$K_{SiC} = \frac{2.311\times10^{-3}}{5.049\times10^{-6} + 130.679\times10^{9} r^2 + 3.738\times10^{24} r^4} \tag{4}$$

The corresponding parameters of the SiO_2 core nanospring under unstressed state (G_{SiO2}=29 GPa, $v = 0.17$ and $d_0 = 25 \times 10^{-9} m$) are plugged into formula (3), and the spring constant of SiO_2 core nanospring (K_{SiO2*}) can be deduced as following:

$$K_{SiO_2^*} = \frac{0.349 \times 10^{-3}}{5.049 \times 10^{-6} + 130.679 \times 10^{9} r^2 + 3.738 \times 10^{24} r^4} \quad (5)$$

Similarly, the spring constant of SiO_2 solid nanospring (K_{SiO2}) with the d_0 of 45 nm under unstressed state can also be illustrated as:

$$K_{SiO_2} = \frac{6.284 \times 10^{-4}}{2.805 \times 10^{-6} + 2.296 \times 10^{10} r^2 + 6.409 \times 10^{23} r^4} \quad (6)$$