

Fabrication of uniform $\text{SnO}_2\text{--SiO}_2\text{--Pt}$ composite nanofibres via co-electrospinning

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Abstract

We successfully fabricated uniform $\text{SnO}_2\text{--SiO}_2\text{--Pt}$ composite nanofibres (NFs) by using a co-electrospinning technique, in which we set up two coaxial capillaries. Morphology control of NFs was investigated, along with their structural properties and chemical compositions. Furthermore, to systematically investigate the morphological changes in $\text{SnO}_2\text{--SiO}_2\text{--Pt}$ composite NFs, the relative weight ratios of the Sn precursor to the Si precursor including the 4 wt% Pt precursor were controlled at 3:1, 1:1, and 1:3. To demonstrate the formation mechanism of the composite NFs, the precursor positions of the shell section and the core section in co-electrospinning were reversed. The resultant composite NFs were investigated by using X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM) with energy dispersive X-ray spectroscopy (EDS), and X-ray photoelectron spectroscopy (XPS). These results showed that in the case of the optimum weight ratio (1:1) of the Sn precursor in the shell section to the Si precursor including the 4 wt% Pt precursor in the core section, SnO_2 and Pt nanoparticles were uniformly grown on SiO_2 NFs, implying the successful formation of uniform $\text{SnO}_2\text{--SiO}_2\text{--Pt}$ composite NFs.

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1. Introduction

One-dimensional (1-D) nanofibres (NFs), which have peculiar optical, electrical, chemical, and electrochemical properties, have gained considerable attention recently for their potential use in many applications such as optics, electronics, biondiagnostics, and energy conversion [1–3]. Several studies have attempted to synthesize various 1-D NFs. In particular, many types of NFs with different morphologies, such as composite, core-shell, hollow, rods, and belts, have been synthesized hitherto [3]. Among the various morphologies of NFs, 1-D composite NFs have received considerable attention because of their useful and unique properties, along with complementary properties in NFs. Thus far, various synthetic methods, such as hydrothermal method, template-directed electrochemical method, chemical bath deposition, and electrospinning, have been proposed for the fabrication of 1-D composite

NFs [4–7]. Among the above-mentioned methods, electrospinning, which has important advantages such as simplicity, low-cost, and mass producibility, is one of the most useful methods for the fabrication of 1-D composite NFs. Previous researchers have mainly studied composite NFs composed of two different phases fabricated using an electrospinning method. For example, Jeong et al. fabricated the $\text{Co}_3\text{O}_4\text{--RuO}_2$ composite NFs via electrospinning and demonstrated their structural properties by performing X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), and transmission electron microscopy (TEM) [8]. Zhao et al. fabricated porous CuO/SnO_2 composite NFs via electrospinning for use in H_2S sensing [9]. Wang et al. fabricated $\text{C/Fe}_3\text{O}_4$ composite NFs for use as anode materials in lithium-ion batteries and demonstrated enhanced reversible capacity and good rate capability [10]. Thus, until now, researchers have mainly studied fabrication of composite NFs composed of two phases using an electrospinning method. However, fabrication and morphology control of composite NFs composed of three different phases using a co-electrospinning technique have not yet

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been realized. Therefore, in this study, we successfully synthesized $\text{SnO}_2\text{--SiO}_2\text{--Pt}$ composite NFs via co-electrospinning and performed morphology control in order to obtain uniform composite NFs. These uniform $\text{SnO}_2\text{--SiO}_2\text{--Pt}$ composite NFs could be utilized in various applications such as Li-ion batteries, electrochemical capacitors, and sensors.

2. Preparation

2.1. Experimental

In order to fabricate composite NFs consisting of three different phases, a co-electrospinning technique, divided by the core-section and shell-section, was employed, as shown in Fig. 1. To confirm the morphological changes in the composite NFs, the relative weight ratios of the Sn precursor to the Si precursor were controlled at 3:1, 1:1, and 1:3 to give samples A, B, and C, respectively. In all the samples, 4 wt% of the Pt precursor was equally added to the Si precursor. In the core section, tetraethylorthosilicate (TEOS, Aldrich) as the Si precursor and chloroplatinic acid hydrate ($\text{H}_2\text{PtCl}_6 \cdot x\text{H}_2\text{O}$, Aldrich) as the Pt precursor were dissolved in N,N-dimethylformamide (DMF, Aldrich), and polyvinylpyrrolidone (PVP, $M_w=1,300,000$ g/mol, Aldrich) as a stabilizer was stirred into the above-dissolved solution for 2 h at room temperature. In the shell section, tin (II) chloride dihydrate (SnCl_2 , Aldrich) as the Sn precursor dissolved in N,N-dimethylformamide (DMF, Aldrich) was mixed with polyvinylpyrrolidone (PVP, $M_w=1,300,000$ g/mol, Aldrich) for 2 h at room temperature. The two coaxial capillaries consist of two parts; one is a 26-gauge inner capillary for the Si and Pt precursors, and the other is an 18-gauge outer capillary for the Sn

precursor, as shown in Fig. 1(a). In addition, the precursor position of the shell section and the core section was reversed in order to investigate the formation mechanism of composite NFs, as shown in Fig. 1(b). This will be discussed later in the results and discussion section. The feeding rates during co-electrospinning were fixed at 0.01 ml/h for the core section and 0.02 ml/h for the shell section. The voltage was maintained at ~ 18 kV for all the samples. The resulting as-spun NFs were heat-treated at 300°C for 2 h in air and then calcined at 500°C for 5 h. Thus, uniform $\text{SnO}_2\text{--SiO}_2\text{--Pt}$ composite NFs were successfully fabricated.

2.2. Characterization

The crystallinity and structural properties of the fabricated NFs were characterized by using an X-ray diffractometer (Rigaku Rint 2500) equipped with Cu K_α radiation. The morphology and composition of all the samples were examined by using a field-emission scanning electron microscope (Hitachi S-4700) and a transmission electron microscope (JEOL 2100F, KBSI Suncheon Center) with energy-dispersive X-ray spectroscopy (EDS). The chemical bonding states of all the samples were examined using an X-ray photoelectron spectroscope (ESCALAB 250) equipped with an Al K_α X-ray source.

3. Results and discussion

Fig. 2 shows XRD data obtained from samples A, B, and C after calcination. The main characteristic diffraction peaks for the SnO_2 phases were observed at $2\theta = \sim 26.6^\circ$, 33.8° , 37.9° , and 51.7° , corresponding to the (110), (101), (200), and (211) planes, respectively, of the tetragonal

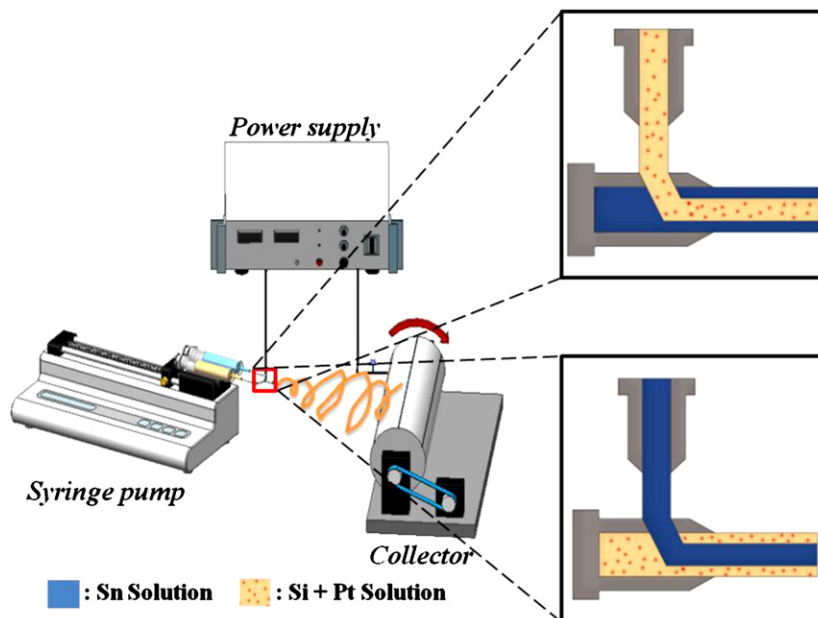


Fig. 1. Schematic of two coaxial capillaries in a co-electrospinning apparatus.

rutile structure of SnO_2 (space group $P4_2/mnm$ [136]; JCPDS card no. 41–1445). Further, the main characteristic diffraction peaks for the Pt phases were observed at $2\theta = \sim 39.7^\circ$ and 46.2° , corresponding to crystalline Pt phases having face-centered cubic structure (space group $Fm3m$ [225]; JCPDS card no. 04–0802). No diffraction peak related to the SiO_2 phases was observed for any of the samples, thus indicating amorphous characteristics. In particular, no diffraction peak shift for SnO_2 and SiO_2 was observed, signifying the existence of composite phases. Thus, the XRD results showed that composite NFs were

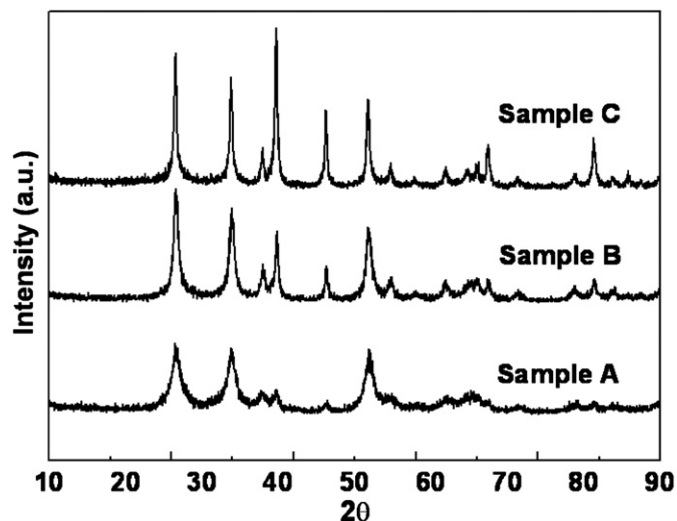


Fig. 2. XRD plots obtained from samples A, B, and C after calcination.

composed of crystalline SnO_2 phases, amorphous SiO_2 phases, and crystalline Pt phases.

Fig. 3 shows the FESEM images for samples A, B, and C before calcination ((a)–(c)) and after calcination ((d)–(f)). The as-spun samples consist of the core section formed by the Si precursor–PVP composite and the Pt precursor–PVP composite and the shell section formed by the Sn precursor–PVP composite. The diameter of the as-spun samples before calcination was in the range of ~ 180 – 230 nm. The diameters of samples A, B, and C after calcination are ~ 70 – 100 nm, ~ 100 – 130 nm, and ~ 100 – 170 nm, respectively. As seen in Fig. 3(d), sample A exhibits small aggregation of SnO_2 nanophases on the SiO_2 NFs because it had a higher loading amount of SnO_2 . Sample B (Fig. 3(e)) exhibits uniform dispersion of SnO_2 nanophases on the Si NFs. Sample C (Fig. 3(f)) exhibits relatively larger aggregations of SnO_2 nanophases on the Si NFs because it had a lower loading amount of SnO_2 . Therefore, uniform composite NFs having three different phases were formed when the weight ratio of the Sn precursor to the Si precursor was 1:1.

Fig. 4 shows the TEM images obtained from samples A, B, and C after calcination. Samples A and B consist of relatively dark, large nanoparticles related to the SnO_2 phases; relatively darker, small nanoparticles related to the Pt phases; and relatively light NFs related to the SiO_2 phases. As shown in Fig. 4(b), sample B exhibits uniform morphology (e.g. grain size and distribution of the SnO_2 phases) of the composite NFs compared to sample A. In particular, as shown in Fig. 4(c), sample C exhibits non-uniform composite NFs having three different phases, i.e.

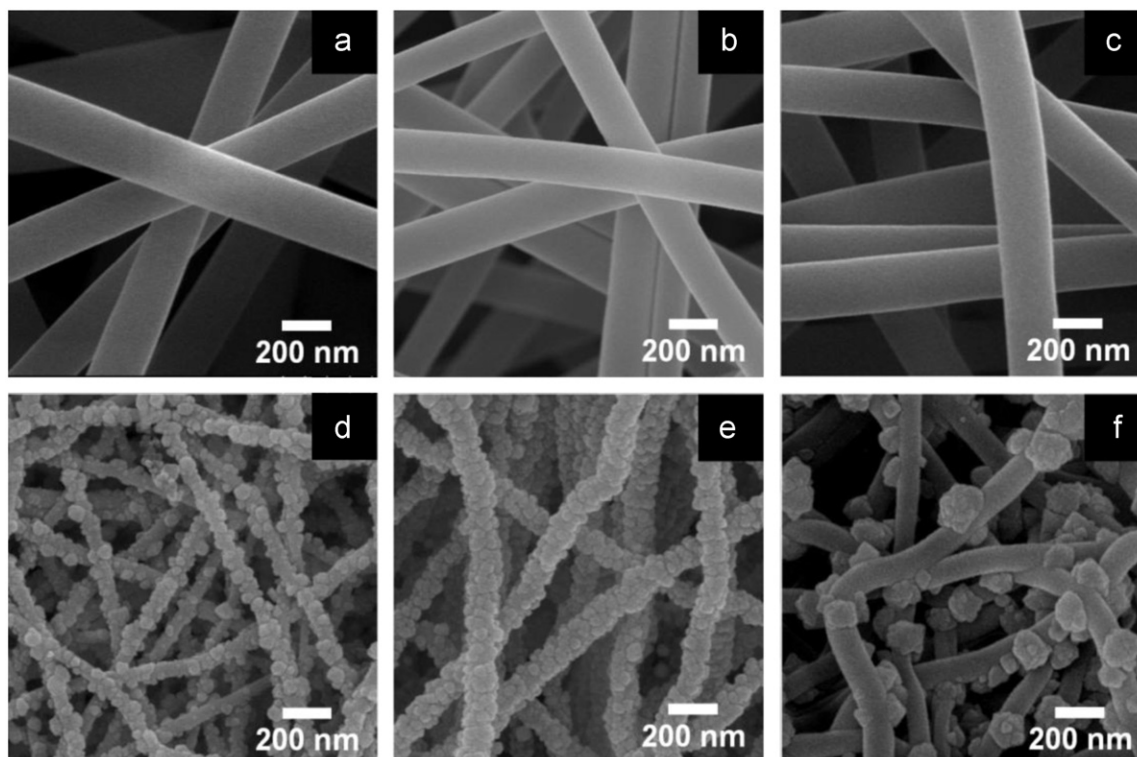


Fig. 3. FESEM images of samples A, B, and C before calcination ((a)–(c)) and after calcination ((d)–(f)).

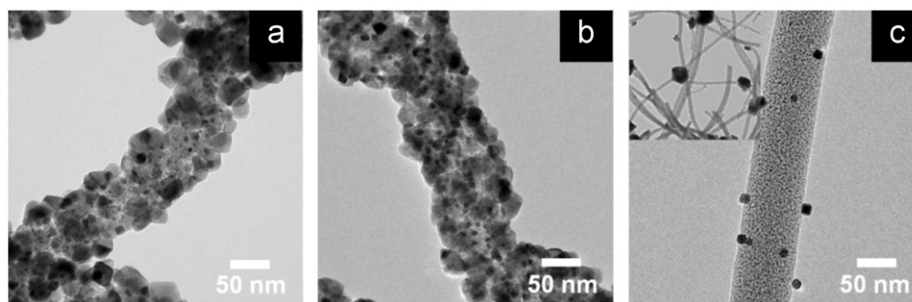


Fig. 4. TEM images of samples A, B, and C after calcination ((a)–(c)).

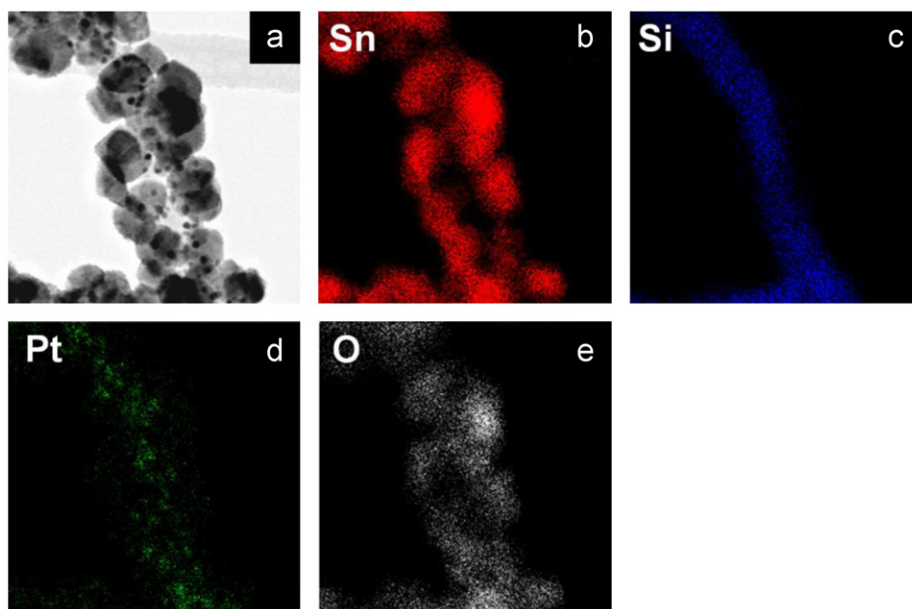


Fig. 5. TEM-EDS mapping data obtained from sample A.

it consists of relatively dark Pt nanoparticles composited on and within the relatively light SiO_2 NFs and the larger SnO_2 aggregation (see the upper-left inset). Therefore, the TEM results indicated that sample B, fabricated via co-electrospinning, consisted of uniform SnO_2 – SiO_2 –Pt composite NFs having three different phases.

To clearly investigate the distributed composition of the Sn, Si, and Pt atoms in the composite NFs, TEM-EDS mapping of sample A was performed, as shown in Fig. 5(a)–(e). The EDS mapping data indicate that Sn atoms form relatively large grains on the NFs, Si atoms form uniform nanoparticles in the 1-D NFs, and Pt atoms form both relatively large grains (SnO_2 phases) and uniform NFs (SiO_2 phases). These results imply that the composite NFs having three different phases are composed of uniformly distributed SnO_2 nanophases grown on the SiO_2 NFs, along with Pt nanophases distributed within the SnO_2 and SiO_2 phases.

To confirm the chemical bonding states and composition of elemental Sn, Si, and Pt, XPS analyses were carried out. Fig. 6(a)–(i) shows the XPS spectra of the Sn $3d$, Si $2p$, and

Pt $4d$ core levels obtained from samples A, B, and C. The XPS spectra for the Sn $3d_{5/2}$ and $3d_{3/2}$ photoelectrons of all the samples were observed at ~ 486.6 and ~ 495.0 eV, which implies that elemental Sn was formed in the SnO_2 phases. The XPS spectra for the Si $2p$ photoelectrons of all the samples were observed at ~ 103.2 eV, indicating that elemental Si was formed in the SiO_2 phases [11]. In addition, the XPS spectra for the Pt $4d_{5/2}$ and $4d_{3/2}$ photoelectrons of all the samples were observed at ~ 316.5 and ~ 333.2 eV, implying the formation of the metallic Pt phases. Thus, the XPS results reveal that Sn, Si, and Pt in all the samples exist as Sn (IV), Si (IV), and Pt (0) states, corresponding to SnO_2 , SiO_2 , and metallic Pt phases, respectively. The XRD, FESEM, TEM with EDS mapping, and XPS analyses confirm that uniform SnO_2 – SiO_2 –Pt composite NFs were successfully synthesized via a co-electrospinning technique.

To further investigate the formation mechanism of the uniform composite NFs (sample B), we changed the position of the precursor solutions relative to the core section and the shell section during co-electrospinning,

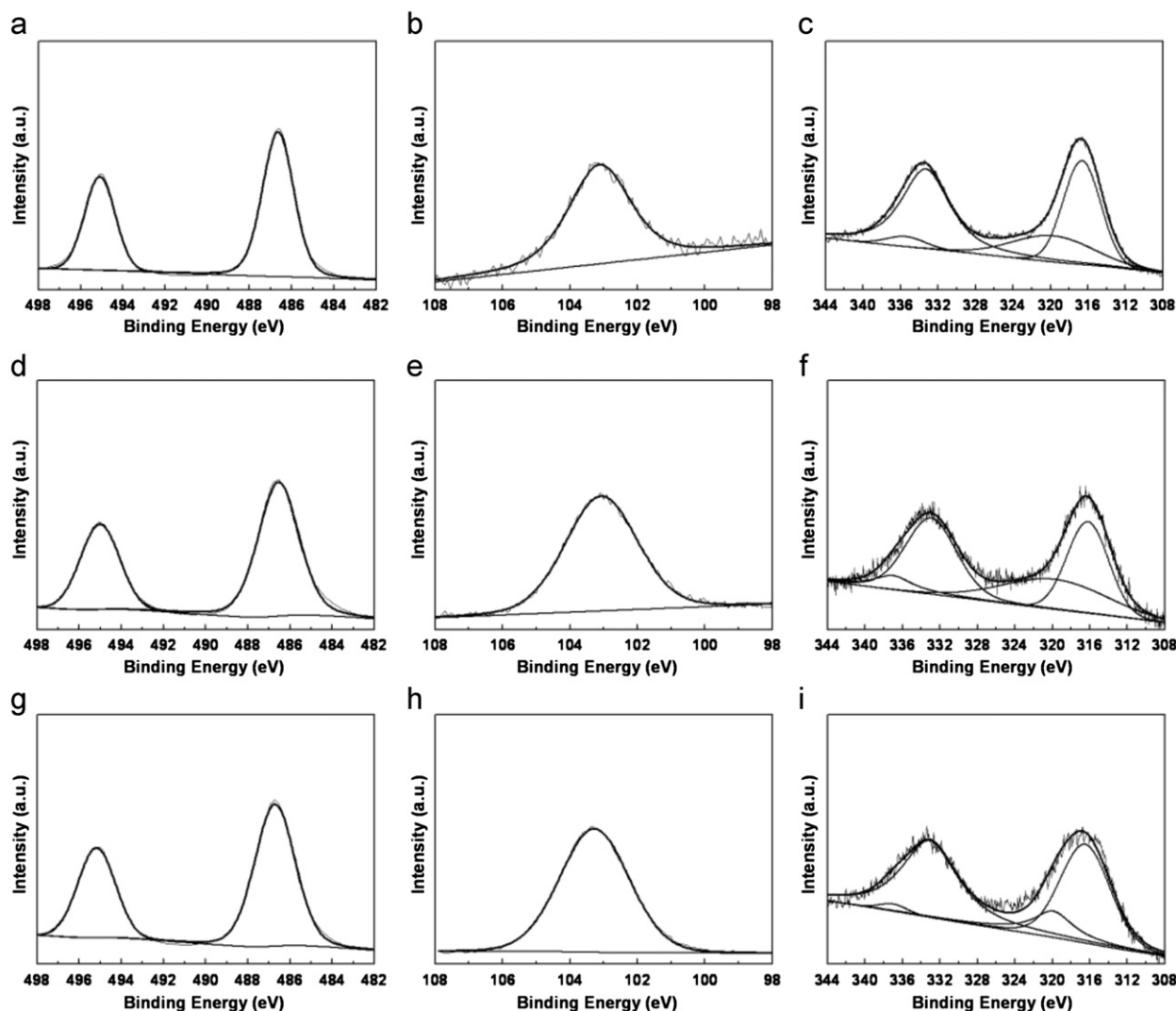


Fig. 6. XPS spectra of the Sn 3d, Si 2p, and Pt 4d core levels for sample A ((a)–(c)), sample B ((d)–(f)), and sample C ((g)–(i)).

from that shown in Fig. 1(a) to that shown in Fig. 1(b). Interestingly, we confirmed morphology changes similar to those seen in sample C, which are indicative of non-uniform composite NFs, as shown in Fig. 7(a). Thus, the formation mechanism for uniform composite NFs could be attributed to the position of the precursor solutions in co-electrospinning. The Si and Pt precursor solutions were placed in the core section, and the Sn precursor solution was placed in the shell section (Fig. 7(b)). After calcination, the SnO₂ nanoparticles were uniformly formed on the SiO₂ NFs (Fig. 3(e)). This is because the Sn precursor in the shell section reacted directly with the oxygen source in the air during calcination. However, when the Sn precursor solution was placed in the core section and the Si and Pt precursor solutions were placed in the shell section (Fig. 7(c)), after calcination, a large aggregation of the SnO₂ nanoparticles was distributed on the SiO₂ NFs (Fig. 7(a)). In this case, the Sn atoms in the core section moved into the shell section and the Si atoms in the shell section moved into the core section during calcination

because Sn atoms tend to oxidize preferentially compared to Si atoms. Thus, Sn atoms moved by diffusion from the core section to the shell section to combine with oxygen in the air during calcinations, then causing the aggregation of Sn atoms. Therefore, in order to synthesize uniform SnO₂–SiO₂–Pt composite NFs having three different phases, it is very important to adjust the position of the precursors and select an optimum weight ratio of the Sn precursor to the Si precursor.

4. Conclusions

Uniform SnO₂–SiO₂–Pt composite NFs were successfully synthesized via co-electrospinning. Their morphology control and structural properties were demonstrated by XRD, FESEM, TEM, TEM–EDS mapping, and XPS analyses. The uniform composite NFs could be obtained by a combination of using the optimum weight ratio (1:1) of the Sn precursor to the Si precursor and adjusting the position of the precursors related to the Sn precursor in the

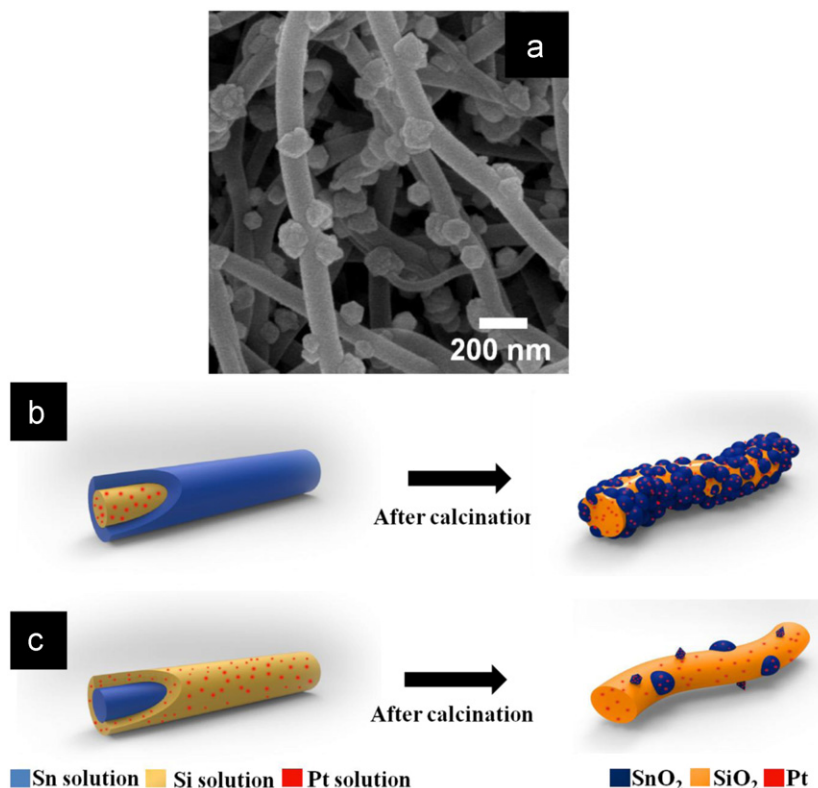


Fig. 7. SEM image of non-uniform composite NFs obtained from an experimental method of Fig. 1(b). (a). Schematic of uniform composite NFs (b) and non-uniform composite NFs (c) depending on the position of the precursor solutions in co-electrospinning.

shell section and the Si–Pt precursor in the core section. The SnO₂ nanophases were uniformly distributed on the SiO₂ NFs together with the Pt nanophases formed within SnO₂ nanophases and SiO₂ NFs. Thus, co-electrospinning could be considered a powerful technique for fabricating uniform SnO₂–SiO₂–Pt composite NFs having three different phases.

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