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Flexible, Freestanding, and Binder-free SnO_x–ZnO/Carbon Nanofiber Composites for Lithium Ion Battery Anodes

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Supporting Information

ABSTRACT: Here, we demonstrate the production of electrospun SnO_x -ZnO polyacrylonitrile (PAN) nanofibers (NFs) that are flexible, freestanding, and binder-free. This NF fabric is flexible and thus can be readily tailored into a coin for further cell fabrication. These properties allow volume expansion of the oxide materials and provide shortened diffusion pathways for Li ions than those achieved using the nanoparticle approach. Amorphous SnO_x -ZnO particles were uniformly dispersed in the carbon NF (CNF). The SnO_x -ZnO CNFs with a Sn:Zn ratio of 3:1 exhibited a superior reversible capacity of 963 mA·h·g⁻¹ after 55 cycles at a current density of 100 mA·g⁻¹, which is three times higher than the capacity of graphite-based anodes. The amorphous NFs



facilitated Li_2O decomposition, thereby enhancing the reversible capacity. ZnO prevented the aggregation of Sn, which, in turn, conferred stable and high discharge capacity to the cell. Overall, the SnO_x -ZnO CNFs were shown to exhibit remarkably high capacity retention and high reversible and rate capacities as Li ion battery anodes.

KEYWORDS: freestanding, carbon nanofiber, SnO_x, ZnO, electrospinning, lithium ion battery

INTRODUCTION

Li ion batteries (LIBs) are highly efficient energy-storage devices, particularly for portable electronics. The efficiency of LIBs is attributed to their high energy capacity and long lifespan.¹ Transition metal oxides, such as LiCoO₂, which is used by Sony, have been very successfully applied as cathode materials.² Other cathode materials include phosphate-based composites, such as LiFePO₄ and LiCoPO₄-carbon.³⁻⁵ The use of silicate-based Li₂MnSiO as a cathode material has also been reported.⁶ In contrast, carbon materials, including graphite, have been commonly used as anode materials for LIBs because of their superior electrical and mechanical properties.⁷ However, these carbon materials suffer from low theoretical specific capacity (graphite = $372 \text{ mA} \cdot \text{h} \cdot \text{g}^{-1}$) for LiC₆ and poor rate capability.⁸ Thus, considerable efforts have been made to improve anode materials. Consequently, various anode materials have been explored, including alloys,⁹ metal oxides,¹⁰ and metal chalcogenides.¹¹ Among these materials, metal oxides have been identified as promising alternatives to carbon materials because of their higher theoretical capacities.¹²

 SnO_2 has been used as an anode material in LIBs because of its nontoxicity, low cost, low operating potential (0.25 V vs Li/Li⁺), and high theoretical capacity. Indeed, the first discharge capacity of SnO_2 is 1498 mA·h·g⁻¹, and its reversible discharge

capacity is 782 mA·h·g⁻¹.^{13,14} However, the major bottlenecks limiting the practical application of SnO₂ include its poor cyclability, considerable irreversible capacity during the first charge and discharge, and electrode pulverization during the Li-Sn alloying and dealloying cycle.¹⁵ To date, numerous studies have been performed to improve the cyclic stability of SnO₂, including preparing nanostructures, creating composites with carbon, blending with more electrochemically active atoms, and restricting the cycling voltage range. SnO is obtained by reducing SnO₂ and is also known to have a high theoretical capacity (approximately 880 mA·h·g⁻¹) but low conductivity.¹⁴ ZnO is a transition metal oxide used in LIB anodes and is unreactive to the environment and low cost and has a theoretical capacity of 978 mA \cdot h·g⁻¹. However, pure ZnO exhibits severe capacity fading and, consequently, deficient cyclic performance because of its large volume changes and low electronic conductivity, similar to SnO₂. Thus, combining SnO₂ and ZnO may overcome the individual materials' shortcomings.

Composite SnO_2 -ZnO structures have been reported to exhibit improved reversible capacity and high performance as

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anode materials; for example, ball-milled ZnO-SnO₂ composites were applied by Belliard and Irvine¹⁶ as anodes for LIBs, and using a ZnO/SnO_2 ratio of 1:2, they achieved a high initial capacity of 1532 mA·h·g⁻¹ and a reversible capacity of 613 mA· $h g^{-1}$. Improved cyclability at low ZnO levels was observed with a milling time of 22 h. Wang et al.¹⁷ reported the layer-by-layer synthesis of ZnO/SnO₂ composite nanowire arrays as anodes for LIBs yielding reliable cyclic stability and high reversible capacity. Indeed, the nanowire composite with a ZnO/SnO₂ ratio of 5:1 showed a high discharge capacity of 1623.5 mA·h· g^{-1} , and its reversible capacity was 552 mA·h· g^{-1} after 30 cycles. Zhao et al.¹⁸ synthesized SnO₂–ZnO nanofibers (NFs) by electrospinning using polyvinylpyrrolidone (PVP) polymer; in this case, ZnO acted a buffer matrix, accommodating the volume change. Similarly, Fang et al.¹⁹ also reported the synthesis of hollow SnO₂/ZnO NFs using PVP polymer and annealing the fibers in air. However, the NFs were brittle and not freestanding, and as a result, binders were used to hold the particles together for further cell fabrication. ZnO incorporated into SnO₂ functions as a buffer, reducing the frequency of strains induced during alloying and dealloying and thereby improving the battery performance.

All of the aforementioned approaches used binders, which act as electrical insulators and, therefore, inevitably hinder the performance and capacity of LIB cells.²⁰ Huang et al.²¹ fabricated a binder-free ZnO/SnO₂ thin film via vacuum-based physical vacuum deposition. Unfortunately, the discharge and reversible capacities of the film were not as high as the films fabricated via non-vacuum-based methods.

Herein, we utilize a combination of SnO_x and ZnO because combining this composite with carbon materials has been shown to mitigate the expansion of metal alloys containing Li.^{22–25} The SnO_x–ZnO NF fabricated in this work is structurally freestanding, and thus, no structural support is needed, minimizing the total weight of the battery. The lightweight nature of this material is advantageous for portable electronics.²⁶ Because the developed NF is freestanding and binder-free, it exhibits high performance, potentially augmenting the energy density of the resulting LIB.²⁷ Although some similar studies have been performed,^{13,27–29} freestanding, flexible, and binder-free SnO_x–ZnO NFs have not been investigated previously.

EXPERIMENTAL METHOD

Freestanding NF Mat Synthesis. Tin(II) acetate (SnAc, Sn(CH₃CO₂)₂; Sigma-Aldrich) and zinc acetate dihydrate (ZnAc, Zn(CH₃COO)₂·2H₂O; 98%; Sigma-Aldrich) were used as metal sources. *N*,*N*-dimethylformamide (DMF; 99.8%; Sigma-Aldrich) was used as the solvent without further purification. Polyacrylonitrile (PAN; M_w = 150 kDa; Sigma-Aldrich) was used as the solute in the electrospinning solution.

First, 8 wt % PAN was dissolved in DMF, and the mixture was stirred for 24 h at 60 °C. Then, SnAc and ZnAc were dissolved in this PAN–DMF solution, and the resulting mixture was again stirred for 24 h at room temperature to form a homogeneous solution. The total amount of metal salt in the PAN solution was 4 wt %, and solutions with varying metal compositions were prepared at Sn:Zn ratios of 25:75, 50:50, and 75:25 (wt %); the obtained carbon NF (CNF) mats are hereafter termed SnZn-1, SnZn-2, and SnZn-3 CNFs, respectively. For comparison, pristine SnO_x CNF and ZnO CNF mats were also synthesized using a single metal source.

The electrospinning setup consisted of a syringe and a needle, a grounded collector, and a high-voltage supply, as shown in Figure 1. The pristine and SnAc–ZnAc solutions were electrospun at room temperature on an aluminum collector 17 cm away from the needle.



Figure 1. Schematic of the electrospinning setup.

The SnAc–ZnAc solution precursor was delivered from a syringe pump at a flow rate adjusted to yield a stable Taylor cone at the end of the needle. Other process parameters were also controlled, as indicated in Table 1. After the electrospinning process was complete, the mats

 Table 1. Operating Conditions for Freestanding Nanofibers
 (i.d., Inner Diameter; o.d., Outer Diameter)

parameter	condition
voltage (kV)	7.8
tip to collector distance (cm)	17
flow rate $(\mu L/h)$	250
needle (mm)	ID = 0.84, OD = 1.27
deposition time (min)	60
stabilization temperature in air (°C)	280
stabilization time (h)	0.5
carbonization temperature (°C)	700
annealing time (h)	2

were annealed in air at 280 °C, and the temperature was ramped up from room temperature to 280 °C at a rate of 5 °C/min. The stabilized mats were further annealed in a tube furnace under flowing Ar at 700 °C for 2 h. The required annealing temperature was achieved by ramping up the temperature from room temperature at a rate of 3 °C/min to carbonize the PAN NFs. This process yielded flexible, freestanding, black SnO_x-ZnO CNF mats, as shown in Figure 1.

The crystalline structures of the films were characterized by X-ray diffraction (XRD; SmartLab, Rigaku). X-ray photoelectron spectroscopy (XPS; Theta Prove Base System, Thermo Fisher Scientific Co.) measurements were conducted to evaluate the chemical states and atomic concentrations of the elements in the films. The surface morphologies and elemental mapping of the fabricated films were evaluated by using a field emission scanning electron microscope (FE-SEM; S-5000, Hitachi, Ltd.) and a transmission electron microscope (TEM; JEM 2100F, JEOL Inc.). A confocal Raman spectrometer (Jasco, NRS-3100) was used to analyze the carbon content and carbon defects in the mats. Thermogravimetric analysis (TGA; SDT Q600, TA Instruments) was performed to evaluate the mats' thermal stabilities.

Electrochemical Tests. The electrochemical performance was measured by using a CR2032 coin-type half-cell, in which carbonized freestanding NF mats were directly applied as the anode without mechanical milling or a slurry-coating process. No current collectors or binders were used in these electrodes. The mat samples were punched into circular electrodes (14 mm diameter). For the reference electrode, a metallic Li sheet was utilized with a microporous polymer separator (Celgard 2400; Celgard, Chungbuk, South Korea). The liquid electrolyte in the cell comprised 1 M LiPF₆ in a solvent mixture of ethylene carbonate (EC), dimethylcarbonate (DMC), and ethyl methyl carbonate (EMC) (1:1:1 by volume) (PuriEL, Soulbrain, Seongnam, South Korea). Galvanostatic discharge/charge curves were acquired between 0 and 3 V at 25 °C using a WBCS3000 battery cycler system (WonATech, Seoul, South Korea). The cells were initially subjected to rate tests at different current densities (10 cycles

each at 100, 200, 500, and 1000 mA·g $^{-1})$, followed by a 15-cycle test at 100 mA·g $^{-1}$.

RESULTS AND DISCUSSION

Figure 2 shows the XRD patterns of pristine SnO_x , ZnO, and the SnO_x -ZnO composites of various compositions, as



Figure 2. XRD patterns of freestanding SnO_x -ZnO CNF mats.

specified in Experimental Method. The pristine SnO_x sample exhibits weak peaks positioned at $2\theta = 30.52^\circ$, 32.03° , and 44.85° , corresponding to the (200), (101), and (211) orientations of SnO_x . The stabilization (air annealing) temperature of 280 °C was not sufficient for ZnO crystallization; furthermore, during carbonization, the flow of Ar also inhibits the oxidation process, resulting in formation of the amorphous

phase in pristine ZnO CNFs. Notably, the XRD patterns of the samples show a broad peak near 25° , corresponding to graphitic carbon obtained from PAN. Except for pristine SnO_x , no sharp peaks related to SnO_x and ZnO were detected in the profiles of the SnO_x –ZnO composite mats. This may have occurred because doping ZnO into SnO_x hinders the crystallization process, resulting in more nanosized or amorphous particles. Thus, all of the mixed oxide samples contained amorphous SnO_x and ZnO particles. The formation of the amorphous phase or nanoparticles facilitates achieving higher rates of Li insertion and extraction.

TEM was used to detect the presence of SnO_x and ZnO particles, as shown in Figure 3a. No discernible trace of nanoparticles was observed in the CNFs, as shown in Figure 3b. The selected-area electron diffraction (SAED) pattern presented in Figure 3c contains no clear diffraction pattern of SnO_x or ZnO, suggesting that both oxides are in amorphous states, as observed using XRD. Energy-dispersive X-ray (EDX; Figure 3d) analysis confirmed the presence of these elements (i.e., C, Sn, Zn, O, and N), as presented in Figure 3e–i, which present the elemental mapping results. These maps demonstrate that the elements are distributed homogeneously along the NF. The SnO_x –ZnO and C contents in the NF were estimated to be approximately 28 and 62 wt %, respectively, based on the TGA shown in Figure S1 in the Supporting Information.

The Raman scattering spectra of the SnO_x -ZnO composite NFs were recorded using a 532 nm laser as the excitation source. The Raman spectra presented in Figure 4 show bands at 1348 and 1586 cm⁻¹, corresponding to the disordered (D) and



Figure 3. Morphology and elemental composition of SnZn-3 observed by TEM: (a and b) TEM images, (c) SAED pattern, (d) EDX analysis, and (e-i) elemental mapping of C, Sn, Zn, O, and N, respectively.



Figure 4. Raman spectra of freestanding SnO_x-ZnO CNF mats.

graphitic (G) carbon phases, respectively, for all samples. The presence of D- and G-bands confirms that PAN was transformed into graphitized carbon at the annealing temperature of 700 °C in Ar. The D-band indicates the presence of sp³ defects in the carbon chain, whereas the G-band corresponds to the in-plane vibrations of sp²-conjugated carbons. The ratio of the intensities of the D- and G-bands (I_D/I_G) for the SnZn-3, SnZn-2, and SnZn-1 mats were calculated to be 1.05, 1.04, and

1.07, respectively. The high $I_{\rm D}/I_{\rm G}$ value (~1.0) indicates increased disorder and poor graphitization in the composite, which is favorable for higher Li storage.²⁸ Increasing the carbonization temperature is known to decrease the disorder and improve both the graphitization and the conductivity of CNF; however, the metal particles are simultaneously aggregated in the CNFs, thereby deteriorating the electrochemical performance of the electrode.^{27,28} Hence, the carbonization temperature was restricted to 700 °C.

Figure 5 shows the high-resolution Sn 3d, Zn 2p, C 1s, and O 1s XPS spectra of the SnO_x-ZnO/CNF mats. The survey spectrum presented in the Supporting Information (Figure S1) shows signals from C, N, O, Sn, and Zn. The high-resolution spectrum (Figure 5a) of Sn contains two peaks at 486.7 and 495.1 eV, which are assigned to Sn $3d_{5/1}$ and Sn $3d_{3/2}$, respectively. Similarly, the peaks at 1021.4 and 1045 eV in Figure 5b correspond to the binding energies of Zn $2p_{3/2}$ and Zn $2p_{1/2}$, respectively. These results confirm that SnO_x and ZnO coexist in the samples. Peaks also appear at 285 and 531 eV in the C 1s and O 1s spectra, as shown in Figure 5c,d, respectively. The atomic concentrations of the elements determined by XPS analysis for all three cases are presented in Table 2, revealing a decrease in the ZnO content and an increase in the SnO_x content.

The morphologies of the SnO_x -ZnO CNF mats are shown in Figure 6. All of the SEM images display the smooth, uniform, long, and continuous fibrous morphology of the NFs, and no apparent differences are observed. The surface morphologies of the samples are free of agglomerated particles, indicating that the ZnO and SnO_x particles are well embedded in the CNF matrix. The average NF diameters were estimated from the SEM images by measuring 100 NFs in each sample: 254, 284,



Figure 5. XPS analysis of a freestanding SnZn-3 CNF mat: (a) Sn 3d, (b) Zn 2p, (c) C 1s, and (d) O 1s.

Table 2. Atomic Concentration of Elements Determined by XPS

	atom	atomic concentrations (at. %)		
elements	SnZn-1	SnZn-2	SnZn-3	
C 1s	76. <u>3</u>	73.8	71.3	
N 1s	13.1	14.3	13.9	
O 1s	8.4	9.1	11.4	
Sn 3d	0.7	1.5	2.4	
Zn 2p	1.5	1.3	1.0	

and 219 nm with standard deviations of 80, 42, and 35 nm for SnZn-1, SnZn-2, and SnZn-3, respectively.

The possible electrochemical reactions between Li and the SnO_x -ZnO CNFs during the lithiation and delithiation processes can be described as follows:

$$SnO_x + 2xLi^+ + 2xe^- \rightarrow Sn + xLi_2O$$
(1)

$$\operatorname{Sn} + x\operatorname{Li}^+ + xe^- \leftrightarrow \operatorname{Li}_x\operatorname{Sn} \qquad x \le 4.4$$
 (2)

$$ZnO + 2Li^{+} + 2e^{-} \rightarrow Zn + Li_{2}O$$
(3)

 $\operatorname{Zn} + x\operatorname{Li}^{+} + xe^{-} \leftrightarrow \operatorname{Li}_{x}\operatorname{Zn} \qquad x \leq 1$ (4)

$$C + xLi^{+} + xe^{-} \leftrightarrow Li_{x}C \tag{5}$$

Based on eqs 1 and 2, 1 mol of SnO_x is expected to react with 4 mol of Li ions to yield 2 mol of Li₂O and 1 mol of Sn when x = 2. Furthermore, 1 mol of Sn will form a Li_xSn alloy with 4.4 mol of Li ions. Thus, almost 8.4 Li ions are used during the first lithiation. However, Li is irreversibly consumed in the first step (eq 1), inactivating the 4 mol of Li and decreasing the Coulombic efficiency. Therefore, if the first reaction is a reversible process, then Li₂O is decomposed by Sn and Zn (eqs 1 and 3),and the theoretical capacity of SnO₂ should increase to 1493 mA·h·g⁻¹ (8.4 mol of Li ions).³⁰ Thus, the decomposition of Li₂O and the presence of amorphous SnO_x and ZnO particles are responsible for the higher specific capacity of SnZn-3 relative to the theoretical capacity of SnO₂.

The Li-storage performance of all freestanding NFs was investigated based on their galvanostatic charge–discharge profiles in the voltage range of 0-3 V at a current density of 100 mA·g⁻¹. The first five capacity-vs-voltage curves of SnZn-3 are shown in Figure 7. In the first discharge process, a typical curve is observed that is related to the insertion of Li ions (lithiation) into the SnZn-3 electrode. Three distinctive steps



Figure 7. First five charge–discharge curves of SnZn-3 at 100 mA \cdot g⁻¹.

can clearly be observed in Figure 7, as indicated by the vertical black tick lines at 1.2, 0.7, and 0.3 V in the discharge (or insertion) curve and the horizontal blue tick marks at 0.2, 0.5, and 1.2 V in the charge (or extraction) curve. The plateau at 0.7 V and ensuing slope account for the majority of the total capacity of approximately 1310 mA·h·g⁻¹. When N = 1, the observed discharge and charge capacities were 1910 and 1400 mA·h·g⁻¹, respectively. The Coulombic efficiency determined from the capacity ratio of delithiation to lithiation was 73.3% for N = 1. When N = 2, the observed capacities were 1328 and 1284 $mA \cdot h \cdot g^{-1}$ for Li insertion and extraction, and the Coulombic efficiency increased rapidly to 95%. However, the difference between the first and second discharge capacities is attributable to a side reaction with the electrolyte, which results in a solid electrolyte layer (SEI) and incomplete decomposition of Li_2O (eqs 1 and 3).^{22,24} The plateau observed in the discharge curve for N = 1 between 1.2 and 0.7 V supports the proposed formation of the SEI layer and is followed by a slope corresponding to lithiation in the SnO_x -ZnO CNFs.

Figure 8 shows the rate capabilities of SnO_x -ZnO CNFs with different SnZn compositions. For SnZn-3, the capacity was very high at 100 mA·g⁻¹ but was lower at higher currents, such as 500 and 1000 mA·g⁻¹. When the current density was increased from 100 mA·g⁻¹ to 200, 500, and 1000 mA·g⁻¹, the corresponding average discharge capacities decreased from 1100 mA·g⁻¹ to 900, 600, and 400 mAh·g⁻¹, respectively. A discharge capacity of up to 1004 mAh·g⁻¹ was retained after 55 cycles when the current density was restored to 100 mA·g⁻¹, as



Figure 6. SEM images of (a) SnZn-1, (b) SnZn-2, and (c) SnZn-3.



Figure 8. Rate capability of SnZn over a voltage range of 0–3.0 V.

shown in Figure 8, demonstrating the high rate capability of SnZn-3 compared to SnZn-2 and SnZn-1. The initial capacities of SnZn-2 and SnZn-1 declined as the amount of ZnO increased because of this component's low electrochemical activity.¹⁸ The overall capacity obtained at a current density of $100 \text{ mA} \cdot \text{g}^{-1}$ was retained for all SnO_x-ZnO samples at different current densities and longer cycling times.

A comparative analysis of SnZn-3 and the pristine cases is presented in Figure 9. The fast capacity fading of pristine SnO_x



Figure 9. Rate capabilities of pristine SnO_x, ZnO, SnZn-3, and CNFs over a voltage range of 0–3.0 V.

and ZnO (Figure 9) is attributed to the formation of aggregated particles and volume expansion, which resulted in poor kinetics of the electrochemical conversion reaction.^{17,18} Notably, the CNFs studied here exhibited superior capacity retention because of the NFs' adequate conductivity. Similar results were obtained by Jin et al.³¹ The improved reversible capacity of SnO_x-ZnO CNF compared to that of pristine SnO_x CNFs can also be ascribed to the reversible electrochemical reaction of Zn (eq 3), which reversibly converts Li_2O to Li^+ and promotes the reoxidation of Sn to SnO during the delithiation process. The presence of Zn nanoparticles in the Li₂O matrix also reduces the aggregation of the Sn particles during alloying and dealloying. Similar effects were previously observed when SnO NFs were doped with Cu, as reported by Chi et al.²⁸ Zhao et al. found that ZnO functions as a soft matrix and reduces the volume expansion during alloying and dealloying.¹⁸ However, as the ZnO content in the SnO_x -ZnO CNFs increased (e.g.,

SnZn-1), the overall capacity of the freestanding mat decreased, possibly because of the low electrochemical activity of ZnO.

Figure 10 shows the cyclic performance of all SnO_x -ZnO electrodes at a current density of 100 mA·g⁻¹. Comparing all of



Figure 10. Cyclic performance and Coulombic efficiency of SnZn at 100 mA $\cdot g^{-1}$.

the SnO_x–ZnO electrodes reveals that the SnZn-3 electrode exhibited high capacity and high reversible capacity (963 mA·h·g⁻¹) after 55 cycles, corresponding to 72% retention of the discharge capacity at N = 2 (1328 mA·h·g⁻¹). The Coulombic efficiencies of all mats were 98–99% after the first five cycles, as shown in Figure 10.

Figure 11 shows TEM images at two different magnifications that revealed that the NF suffered no discernible deterioration



Figure 11. TEM images after 55 cycles: (a) low- and (b) high-magnification images.

or damage, even after 55 cycles. Table 3 presents a comparison of the methods used to prepare SnO_2 -ZnO electrodes reported previously. This table clearly shows that the composites obtained here exhibited the highest capacity and better reversible capacity. The remarkably high capacity retention, superior reversible and rate capacities, and free-standing nature and flexibility of the SnO_x -ZnO CNF composite prepared in this work make it a suitable anode material for LIBs.

CONCLUSIONS

Freestanding hybrid nanocomposite mats of optimized SnO_x -ZnO CNFs were fabricated by electrospinning followed by annealing. These nanocomposite mats exhibited improved rate and reversible capacities relative to the pristine fibers. XRD and TEM analyses indicated that the amorphous SnO_x and ZnO particles were well embedded in the CNFs. The SnZn-3 electrode exhibited the highest first discharge and charge

Table 3. Compariso	n of Specific Capacities	Obtained	1 in Present Study with Tha	t of Reported SnO _x -ZnO An	lodes		
composn	electrode prepared	flexibility	first discharge capacity $(mA \cdot h \cdot g^{-1})$	first reversible capacity $(mA \cdot h \cdot g^{-1})$	reversible capacity (Nth) ($mA \cdot h \cdot g^{-1}$)	current rate $(mA \cdot g^{-1})$	refs
SnO ₂ :ZnO (2:1)	nanoparticles with binder	ou	1532	613		0.11 mA/cm^2	16
$SnO_2:ZnO$ (5:1)	nanowires with binder	ou	1623	840.7	552 (30)	120	17
$SnO_2:ZnO$	nanoparticles with binder	ou	1540	813	497 (40)	120	15
$SnO_2:ZnO$ (1:1)	nanofibers with binder	ou	1303	891	546.5 (100)	100	19
$SnO_2:ZnO$	thin film without binder	ou	758	740	450 (42)	50	21
$SnO_2:ZnO$ (2:1)	nanofibers with binder	ou	1417	800	430.6 (20)	100	18
SnO _x :ZnO/CNF (3:1)	nanofibers without binder	yes	1910	1328	963 (55)	100	present study

capacities (1910 and 1400 mA·h·g⁻¹, respectively) and a superior reversible capacity of 963 mA·h·g⁻¹ after 55 cycles at a current density of 100 mA·g⁻¹. Evaluating the effects of different weight percentages of ZnO in the SnO_x –ZnO NFs revealed that the SnZn-2 electrode was more stable at high current densities than SnZn-3. The initial Coulombic efficiencies of all mats were 72–73% and increased to 99% after the first five cycles. Overall, these freestanding, flexible mats provide higher Coulombic efficiencies and reversible capacities, making them prospective candidates as anode materials for LIBs.

ASSOCIATED CONTENT

Supporting Information

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TGA curves (PDF)

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Notes

The authors declare no competing financial interest.

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