# Supporting Information

# Functional fiber materials to smart fiber devices

*Chuanrui Chen, Jianyou Feng, Jiaxin Li, Yue Guo, Xiang Shi, Huisheng Peng**

*State Key Laboratory of Molecular Engineering of Polymers, Department of Macromolecular Science, and Laboratory of Advanced Materials, Fudan University, Shanghai 200438, China; E-mail: penghs@fudan.edu.cn.*

**Table S1.** Examples of recently reported fiber supercapacitors.

| Electrode material | Device structure | Specific capacitance | Electrolyte | Energy density<br>Power density | Notes |
|---|---|---|---|---|---|
| Plastic/ZnO NWs[1] | Twisted | 2.4 mF/cm$^2$ | PVA/$H_3PO_4$ | $2.7\times10^{-8}$ Wh/cm$^2$<br>$1.4\times10^{-5}$ W/cm$^2$ | Flexible |
| CNT/$MnO_2$[2] | Twisted | 13.31 F/g | PVA/$H_3PO_4$ | $1.73\times10^{-3}$ Wh/cm$^3$<br>0.79 W/cm$^3$ | N/A |
| CNT[3] | Coaxial | 59 F/g | PVA/$H_3PO_4$ | 1.88 Wh/kg<br>755.9 W/kg | Flexible |
| Rubber/CNT/OMC[4] | Coaxial | 41.4 F/g | PVA/$H_3PO_4$ | N/A | Flexible, stretchable |
| GO/CMC/CNT[5] | Coaxial | 177 mF/cm$^2$ | PVA/$H_3PO_4$ | $3.84\times10^{-6}$ Wh/cm$^2$<br>$2\times10^{-5}$ W/cm$^2$ | Flexible |
| CNT/PANI[6] | Twisted | 274 F/g | PVA/$H_3PO_4$ | N/A | Flexible, weavable |
| CNT/PANI[7] | Parallel | 255.5 F/g | PVA/$H_3PO_4$ | 12.75 Wh/kg<br>1494 W/kg | Flexible, weavable |
| SWNT/rGO[8] | Parallel | 300 F/cm$^3$ (E)[a] | PVA/$H_3PO_4$ | $6.3\times10^{-3}$ Wh/cm$^3$<br>1.085 W/cm$^3$ | Flexible, weavable |
| rGO/$MnO_2$/PPy[9] | Parallel | 411 mF/cm$^2$ (E)[a] | PVA/$H_3PO_4$ | $1.1\times10^{-3}$ Wh/cm$^3$<br>0.16 W/cm$^3$ | Flexible, weavable |
| $MoS_2$-rGO/ MWCNT[10] | Twisted | 4.8 F/cm$^3$ | PVA/$H_2SO_4$ | N/A | Flexible, weavable |
| Carbon/$MnO_2$/PPy CF/$V_2O_5$/PANI[11] | Parallel | 0.613 F/cm$^2$ | LiCl | $0.340\times10^{-3}$ Wh/cm$^2$<br>$30\times10^{-3}$ W/cm$^2$ | Flexible |
| Cotton/Ni/rGO[12] | Parallel | 311 F/g | PVA/LiCl | $6.1\times10^{-3}$ Wh/cm$^3$<br>1.4 W/cm$^3$ | Flexible, weavable, |

| | | | | | |
|---|---|---|---|---|---|
| CNT/$MnO_2$/PPy[13] | Coaxial | 60.435 mF/cm | PVA/KOH | $1.888\times10^{-5}$ Wh/cm$^2$<br>$1.62\times10^{-3}$ W/cm$^2$ | Flexible, stretchable |
| CF/$MnO_2$<br>CF/graphene[14] | Parallel | 87.1 F/g | PVA/LiCl | 27.2 Wh/kg<br>979.7 W/kg | Flexible, weavable |
| rGO/PEDOT:PSS[15] | Parallel | 304.5 mF/cm | PVA/$H_3PO_4$ | $27.1\times10^{-6}$ Wh/cm$^2$<br>$66.5\times10^{-6}$ W/cm$^2$ | Flexible, weavable |
| Urethane/cotton/<br>CNT/PPy[16] | Twisted | 69 mF/cm$^2$ | PVA/$H_3PO_4$ | $6.13\times10^{-6}$ Wh/cm$^2$<br>$1.33\times10^{-4}$ W/cm$^2$ | Flexible, weavable |
| MWCNT/rGO/PPy[17] | Parallel | 25.9 F/cm$^3$ (E)[a] | PVA/$H_3PO_4$ | $9.4\times10^{-4}$ Wh/cm$^3$<br>$7.32\times10^{-3}$ W/cm$^3$ | Flexible, weavable |
| CF/$MnO_2$<br>CF/$MoO_3$[18] | Twisted | 4.86 mF/cm$^2$ | KOH/PVA | $2.70\times10^{-3}$ Wh/cm$^2$<br>$5.3\times10^{-4}$ W/cm$^2$ | Flexible |
| CNT/TiN/MnOx<br>CNT/TiN/carbon[19] | Twisted | 36 F/cm$^3$ | EMIMTFSI/<br>PVDF/HFP | $6.12\times10^{-2}$ Wh/cm$^3$<br>0.2 W/cm$^3$ | Flexible |
| CF[20] | Twisted | 25 mF/cm$^2$ | PVA/$H_3PO_4$ | $3.5\times10^{-6}$ Wh/cm$^2$<br>$4\times10^{-6}$ W/cm$^2$ | Flexible, weavable |
| rGO/PEDOT:PSS<br>/PVA[21] | Parallel | 281.2 F/g | PVA /$H_2SO_4$ | N/A | Flexible, weavable, stretchable |
| Ni/VGNs/<br>$MnO_2$[22] | Twisted | 56 mF/cm$^2$ | CMC/$Na_2SO_4$ | $7.7\times10^{-3}$ Wh/cm$^2$<br>$5\times10^{-3}$ Wh/cm$^2$ | Flexible, weavable |
| Polymer/CNT/<br>PEDOT:PSS/$MnO_2$<br>CNT/PPy[23] | Coaxial | 3.16 F/cm$^3$ | PVA/LiCl | $1.42\times10^{-3}$ Wh/cm$^3$<br>$5\times10^{-3}$ W/cm$^3$ | Flexible, weavable, stretchable |
| CNT/PEDOT:PSS<br>/$MnO_2$/Ag NW[24] | Parallel | 63.5 F/cm$^3$ | Chitosan/<br>PVA/$LiClO_4$ | $5.5\times10^{-3}$ Wh/cm$^3$<br>0.48 W/cm$^3$ | Flexible, weavable |

**Abbreviation**: ZnO NWs: zinc oxide nanowires, PVA: poly(vinyl alcohol), $H_3PO_4$: phosphoric acid, CNT: carbon nanotube, $MnO_2$: manganese dioxide, OMC: ordered microporous carbon, GO: graphene oxide, CMC: carboxymethyl cellulose sodium, PANI: polyaniline, SWNT: single-walled carbon nanotube, rGO: reduced graphene oxide, PPy: polypyrrole, $MoS_2$: molybdenum disulfide, MWCNT: multi-walled carbon nanotube, $H_2SO_4$:

sulfuric acid, CF: carbon fiber, $V_2O_5$: vanadic oxide, LiCl: lithium chloride, Ni: nickel, KOH: potassium hydroxide, $MoO_3$: molybdenum trioxide, EMIMTFSI: 1-ethyl-3-methyl-imidazolium bis(trifluoromethyl sulfonyl)imide, PVDF: polyvinylidene fluoride, HFP: hexafluoropropylene, TiN: titanium nitride, PEDOT:PSS: poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate), VGNs: vertical graphene nanosheets, $Na_2SO_4$: sodium sulfate, Ag NW: silver nanowire, $LiClO_4$: lithium perchlorate; N/A: None.

[a]: Specific capacitance of the electrodes.

**Table S2.** Examples of recently reported fiber batteries.

| Type | Cathode | Anode | Working Voltage | Specific capacity | Flexibility |
|---|---|---|---|---|---|
| Li-ion[25] | Al wire/$LiCoO_2$ | Cu wire/Ni-Sn | 2.5–4.2 V | 1 mAh/cm at 0.1 A/cm | can be bended and twisted |
| Li-ion[2] | MWCNT/$MnO_2$ | Li wire | 1.5–4.3 V | 109.62 mAh/$cm^3$ at $5 \times 10^{-4}$ mA | N/A |
| Li-ion[26] | MWCNT/ $LiMn_2O_4$ | MWCNT/ $Li_4Ti_5O_{12}$ | 1.5–3.3 V | 138 mAh/g at 0.01 mA | 1000 bending cycles; 200 cycles stretching, at a strain of 100 % |
| Li-ion[27] | MWCNT/ $LiMn_2O_4$ | MWCNT/ $Li_4Ti_5O_{12}$ | 1.5–3.2 V | 91.3 mAh/g at 0.1 mA/cm | 100 cycles stretching, at 100% strain |
| Li-ion[28] | CNT/$LiMn_2O_4$ hybrid fiber | CNT/$Li_4Ti_5O_{12}$ hybrid fiber | 1.8–3.0 V | 92.4 mAh/g at 0.1 mA/cm | 300 cycles stretching, at 50% strain |
| Li-ion[29] | CNT/$LiMn_2O_4$ | CNT/Si/CNT | 2.0–4.3 V | 106.5 mAh/g at 1 C rate | can be woven into a flexible textile |
| Aqueous Li-ion[30] | CNT/$LiMn_2O_4$ | CNT/PI | 0–2.5 V | 101 mA h/g even at 100 C rate | can be bent, folded and twisted into various architectures |
| Aqueous Na-ion[31] | CNT/$Na_{0.44}MnO_2$ | CNT/ $NaTi_2(PO_4)_3$@C | 0–1.6 V | 46 mAh/g at 0.1 A/g | bending at 180° for 100 times |
| Aqueous Zn-ion[32] | CNT/$MnO_2$ | CNT/Zn | 0.8–1.85 V | 302.1 mAh/g at 60 mA/g | can be bent, knotted, and twisted |
| Al-$O_2$[33] | CNT/silver-nanoparticle sheets | Al spring | 0.8–1.7 V | 935 mAh/g at 0.5 mA/$cm^2$ | flexible |
| Li-$O_2$[34] | aligned CNT sheet | Li wire | 2.0–4.8 V | 12470 mAh/g at 1400 mA/g | 100 bending cycles |

| | | | | | |
|---|---|---|---|---|---|
| Li-$O_2$[35] | CNT sheet | Lithiated silicon/ CNT hybrid fiber | 2.1–4.0 V | 500 mAh/g at 0.1 mA | 20000 bending cycles |
| Li-$O_2$[36] | stainless-steel mesh/N-CNTs | Li rod | N/A | 9299 mAh/g at 500 mA/g | 5000 rounds of bending and stretching |

**Abbreviation**: $LiCoO_2$: lithium cobalt oxide, $LiMn_2O_4$: lithium manganate, $Li_4Ti_5O_{12}$: lithium titanate, PI: polyimide.

**REFERENCES**


(1) Bae, J.; Song, M. K.; Park, Y. J.; Kim, J. M.; Liu, M.; Wang, Z. L. Fiber Supercapacitors Made of Nanowire-Fiber Hybrid Structures for Wearable/Flexible Energy Storage. *Angew. Chem. Int. Ed.* **2011**, *50*, 1683–1687.

(2) Ren, J.; Li, L.; Chen, C.; Chen, X.; Cai, Z.; Qiu, L.; Wang, Y.; Zhu, X.; Peng, H. Twisting Carbon Nanotube Fibers for Both Wire-Shaped Micro-Supercapacitor and Micro-Battery. *Adv. Mater.* **2013**, *25*, 1155–1159.

(3) Chen, X.; Qiu, L.; Ren, J.; Guan, G.; Lin, H.; Zhang, Z.; Chen, P.; Wang, Y.; Peng, H. Novel Electric Double-Layer Capacitor with a Coaxial Fiber Structure. *Adv. Mater.* **2013**, *25*, 6436–6441.

(4) Yang, Z.; Deng, J.; Chen, X.; Ren, J.; Peng, H. A Highly Stretchable, Fiber-Shaped Supercapacitor. *Angew. Chem. Int. Ed.* **2013**, *52*, 13453–13457.

(5) Kou, L.; Huang, T.; Zheng, B.; Han, Y.; Zhao, X.; Gopalsamy, K.; Sun, H.; Gao, C. Coaxial Wet-Spun Yarn Supercapacitors for High-Energy Density and Safe Wearable Electronics. *Nat. Commun.* **2014**, *5*, 3754.

(6) Cai, Z.; Li, L.; Ren, J.; Qiu, L.; Lin, H.; Peng, H. Flexible, Weavable and Efficient Microsupercapacitor Wires Based on Polyaniline Composite Fibers Incorporated with Aligned Carbon Nanotubes. *J. Mater. Chem. A* **2013**, *1*, 258–261.

(7) Chen, X.; Lin, H.; Deng, J.; Zhang, Y.; Sun, X.; Chen, P.; Fang, X.; Zhang, Z.; Guan, G.; Peng, H. Electrochromic Fiber-Shaped Supercapacitors. *Adv. Mater.* **2014**, *26*, 8126–8132.

(8) Yu, D.; Goh, K.; Wang, H.; Wei, L.; Jiang, W.; Zhang, Q.; Dai, L.; Chen, Y. Scalable Synthesis of Hierarchically Structured Carbon Nanotube–Graphene Fibres for Capacitive Energy Storage. *Nat. Nanotechnol.* **2014**, *9*, 555–562.

(9) Huang, Y.; Hu, H.; Huang, Y.; Zhu, M.; Meng, W.; Liu, C.; Pei, Z.; Hao, C.; Wang, Z.; Zhi, C. From Industrially Weavable and Knittable Highly Conductive Yarns to Large Wearable Energy Storage Textiles. *ACS Nano* **2015**, *9*, 4766–4775.

(10) Sun, G.; Zhang, X.; Lin, R.; Yang, J.; Zhang, H.; Chen, P. Hybrid Fibers Made of Molybdenum Disulfide, Reduced Graphene Oxide, and Multi-Walled Carbon Nanotubes for Solid-State, Flexible, Asymmetric Supercapacitors. *Angew. Chem. Int. Ed.* **2015**, *54*, 4651–4656.

(11) Liu, W.; Liu, N.; Shi, Y.; Chen, Y.; Yang, C.; Tao, J.; Wang, S.; Wang, Y.; Su, J.; Li, L.; et al. A Wire-Shaped Flexible Asymmetric Supercapacitor Based on Carbon Fiber Coated with a Metal Oxide and a Polymer. *J. Mater. Chem. A* **2015**, *3*, 13461–13467.

(12) Liu, L.; Yu, Y.; Yan, C.; Li, K.; Zheng, Z. Wearable Energy-Dense and Power-Dense Supercapacitor Yarns Enabled by Scalable Graphene–Metallic Textile Composite Electrodes. *Nat. Commun.* **2015**, *6*, 7260.

(13) Yu, J.; Lu, W.; Smith, J. P.; Booksh, K. S.; Meng, L.; Huang, Y.; Li, Q.; Byun, J.-H.; Oh, Y.; Yan, Y.; et al. A High Performance Stretchable Asymmetric Fiber-Shaped Supercapacitor with a Core-Sheath Helical Structure. *Adv. Energy Mater.* **2017**, *7*, 1600976.

(14) Yu, N.; Yin, H.; Zhang, W.; Liu, Y.; Tang, Z.; Zhu, M.-Q. High-Performance Fiber-Shaped All-Solid-State Asymmetric Supercapacitors Based on Ultrathin $MnO_2$ Nanosheet/Carbon Fiber Cathodes for Wearable Electronics. *Adv. Energy Mater.* **2016**, *6*, 1501458.

(15) Qu, G.; Cheng, J.; Li, X.; Yuan, D.; Chen, P.; Chen, X.; Wang, B.; Peng, H. A Fiber Supercapacitor with High Energy Density Based on Hollow Graphene/Conducting Polymer Fiber Electrode. *Adv. Mater.* **2016**, *28*, 3646–3652.

(16) Sun, J.; Huang, Y.; Fu, C.; Wang, Z.; Huang, Y.; Zhu, M.; Zhi, C.; Hu, H. High-Performance Stretchable Yarn Supercapacitor Based on PPy@CNTs@Urethane Elastic Fiber Core Spun Yarn. *Nano Energy* **2016**, *27*, 230–237.

(17) He, X.; Zi, Y.; Guo, H.; Zheng, H.; Xi, Y.; Wu, C.; Wang, J.; Zhang, W.; Lu, C.; Wang, Z. L. A Highly Stretchable Fiber-Based Triboelectric Nanogenerator for Self-Powered Wearable Electronics. *Adv. Funct. Mater.* **2017**, *27*, 1604378.

(18) Noh, J.; Yoon, C.-M.; Kim, Y. K.; Jang, J. High Performance Asymmetric Supercapacitor Twisted from Carbon Fiber/$MnO_2$ and Carbon Fiber/$MoO_3$. *Carbon* **2017**, *116*, 470–478.

(19) Pan, Z.; Yang, J.; Zhang, Q.; Liu, M.; Hu, Y.; Kou, Z.; Liu, N.; Yang, X.; Ding, X.; Chen, H.; et al. All-Solid-State Fiber Supercapacitors with Ultrahigh Volumetric Energy Density and Outstanding Flexibility. *Adv. Energy Mater.* **2019**, *9*, 1802753.

(20) Lee, J.; An, G. H. Surface-Engineered Flexible Fibrous Supercapacitor Electrode for Improved Electrochemical Performance. *Appl. Surf. Sci.* **2021**, *539*, 148290.

(21) Xu, T.; Yang, D.; Zhang, S.; Zhao, T.; Zhang, M.; Yu, Z.-Z. Antifreezing and Stretchable All-Gel-State Supercapacitor with Enhanced Capacitances Established by Graphene/PEDOT-Polyvinyl Alcohol Hydrogel Fibers with Dual Networks. *Carbon* **2021**, *171*, 201–210.

(22) Zhou, Y.; Cheng, X.; Huang, F.; Sha, Z.; Han, Z.; Chen, J.; Yang, W.; Yu, Y.; Zhang, J.; Peng, S.; et al. Hierarchically Structured Electrodes for Moldable Supercapacitors by Synergistically Hybridizing Vertical Graphene Nanosheets and MnO2. *Carbon* **2021**, *172*, 272–282.

(23) Pan, Z.; Yang, J.; Li, L.; Gao, X.; Kang, L.; Zhang, Y.; Zhang, Q.; Kou, Z.; Zhang, T.; Wei, L.; et al. All-in-One Stretchable Coaxial-Fiber Strain Sensor Integrated with High-Performing Supercapacitor. *Energy Stor. Mater.* **2020**, *25*, 124–130.

(24) Hong, Y.; Cheng, X.-L.; Liu, G.-J.; Hong, D.-S.; He, S.-S.; Wang, B.-J.; Sun, X.-M.; Peng, H.-S. One-Step Production of Continuous Supercapacitor Fibers for a Flexible Power Textile. *Chin. J. Polym. Sci.* **2019**, *37*, 737–743.

(25) Kwon, Y. H.; Woo, S.-W.; Jung, H.-R.; Yu, H. K.; Kim, K.; Oh, B. H.; Ahn, S.; Lee, S.-Y.; Song, S.-W.; Cho, J.; et al. Cable-Type Flexible Lithium Ion Battery Based on Hollow Multi-Helix Electrodes. *Adv. Mater.* **2012**, *24*, 5192–5197.

(26) Ren, J.; Zhang, Y.; Bai, W.; Chen, X.; Zhang, Z.; Fang, X.; Weng, W.; Wang, Y.; Peng, H. Elastic and Wearable Wire-Shaped Lithium-Ion Battery with High Electrochemical Performance. *Angew. Chem. Int. Ed.* **2014**, *126*, 7998–8003.

(27) Zhang, Y.; Bai, W.; Ren, J.; Weng, W.; Lin, H.; Zhang, Z.; Peng, H. Super-Stretchy Lithium-Ion Battery Based on Carbon Nanotube Fiber. *J. Mater. Chem. A* **2014**, *2*, 11054–11059.

(28) Zhang, Y.; Bai, W.; Cheng, X.; Ren, J.; Weng, W.; Chen, P.; Fang, X.; Zhang, Z.; Peng, H. Flexible and Stretchable Lithium-Ion Batteries and Supercapacitors Based on Electrically Conducting Carbon Nanotube Fiber Springs. *Angew. Chem. Int. Ed.* **2014**, *53*, 14564–14568.

(29) Weng, W.; Sun, Q.; Zhang, Y.; Lin, H.; Ren, J.; Lu, X.; Wang, M.; Peng, H. Winding Aligned Carbon Nanotube Composite Yarns into Coaxial Fiber Full Batteries with High Performances. *Nano Lett.* **2014**, *14*, 3432–3438.

(30) Zhang, Y.; Wang, Y.; Wang, L.; Lo, C.-M.; Zhao, Y.; Jiao, Y.; Zheng, G.; Peng, H. A Fiber-Shaped Aqueous Lithium Ion Battery with High Power Density. *J. Mater. Chem. A* **2016**, *4*, 9002–9008.

(31) Guo, Z.; Zhao, Y.; Ding, Y.; Dong, X.; Chen, L.; Cao, J.; Wang, C.; Xia, Y.; Peng, H.; Wang, Y. Multi-Functional Flexible Aqueous Sodium-Ion Batteries with High Safety. *Chem* **2017**, *3*, 348–362.

(32) Li, H.; Liu, Z.; Liang, G.; Huang, Y.; Huang, Y.; Zhu, M.; Pei, Z.; Xue, Q.; Tang, Z.; Wang, Y.; et al. Waterproof and Tailorable Elastic Rechargeable Yarn Zinc Ion Batteries by a Cross-Linked Polyacrylamide Electrolyte. *ACS Nano* **2018**, *12*, 3140–3148.

(33) Xu, Y.; Zhao, Y.; Ren, J.; Zhang, Y.; Peng, H. An All-Solid-State Fiber-Shaped Aluminum–Air Battery with Flexibility, Stretchability, and High Electrochemical Performance. *Angew. Chem. Int. Ed.* **2016**, *128*, 8111–8114.

(34) Zhang, Y.; Wang, L.; Guo, Z.; Xu, Y.; Wang, Y.; Peng, H. High-Performance Lithium–Air Battery with a Coaxial-Fiber Architecture. *Angew. Chem. Int. Ed.* **2016**, *55*, 4487–4491.

(35) Zhang, Y.; Jiao, Y.; Lu, L.; Wang, L.; Chen, T.; Peng, H. An Ultraflexible Silicon–Oxygen Battery Fiber with High Energy Density. *Angew. Chem. Int. Ed.* **2017**, *56*, 13741–13746.

(36) Yang, X.-Y.; Xu, J.-J.; Chang, Z.-W.; Bao, D.; Yin, Y.-B.; Liu, T.; Yan, J.-M.; Liu, D.-P.; Zhang, Y.; Zhang, X.-B. Blood-Capillary-Inspired, Free-Standing, Flexible, and Low-Cost Super-Hydrophobic N-CNTs@SS Cathodes for High-Capacity, High-Rate, and Stable Li-Air Batteries. *Adv. Energy Mater.* **2018**, *8*, 1702242.