



# Electrical energy harvesting from ferritin bistructured carbon nanotube yarn

Hyunsoo Kim<sup>a</sup>, Jong Woo Park<sup>a</sup>, Jae Sang Hyeon<sup>a</sup>, Hyeon Jun Sim<sup>a</sup>, Yongwoo Jang<sup>a</sup>,  
Yujin Shim<sup>a</sup>, Chi Huynh<sup>b</sup>, Ray H. Baughman<sup>c</sup>, Seon Jeong Kim<sup>a,\*</sup>

<sup>a</sup> Center for Self-powered Actuation, Department of Biomedical Engineering, Hanyang University, Seoul, 04763, South Korea

<sup>b</sup> Lintec of America Nano-Science & Technology Center Richardson, TX, 75081, United States

<sup>c</sup> Alan G. MacDiarmid NanoTech Institute, University of Texas at Dallas, Richardson, TX, 75083, United States

## ARTICLE INFO

### Keywords:

Multi-walled carbon nanotube  
Ferritin  
Energy harvesting  
Yarn  
Bioelectronics  
Implantable device

## ABSTRACT

Various studies about harvesting energy for future energy production have been conducted. In particular, replacing batteries in implantable medical devices with electrical harvesting is a great challenge. Here, we have improved the electrical harvesting performance of twisted carbon nanotube yarn, which was previously reported to be an electrical energy harvester, by bistructuring positively charged ferritin protein in a biofluid environment. The harvester electrodes are made by bistructuring ferritin (40 wt%) in carbon nanotube yarn and twisting it into a coiled structure, which provides stretchability. The coiled ferritin/carbon nanotube yarn generated a 2.8-fold higher peak-to-peak open circuit voltage (OCV) and a 1.5-fold higher peak power than that generated by bare carbon nanotube yarn in phosphate-buffered saline (PBS) buffer. The improved performance is the result of the increased capacitance change and the shifting of the potential of zero charges that are induced by the electrochemically capacitive, positively charged ferritin. As a result, we confirm that the electrical performance of the carbon nanotube harvester can be improved using biomaterials. This carbon nanotube yarn harvester, which contains protein, has the potential to replace batteries in implantable devices.

## 1. Introduction

Various energy harvesting studies have been conducted to address the need for supplying continuous electrical energy to electronic devices without a battery (Chen et al., 2016, 2020; Chen and Wang, 2017; Cottrill et al., 2018; Dong et al., 2017; Guo et al., 2016; Han et al., 2019; Hinchet et al., 2019; Jang et al., 2019; Pu et al., 2017; Ryu et al., 2019; Zhang et al., 2016, 2020). In particular, because a battery needs to be replaced in implanted devices, such as cardiac pacemakers, energy harvesting technologies that can eliminate batteries are considered vital. Although piezoelectric and triboelectric harvesters have been attempted for implantable power, it has still limitations in the service life and the bulky size (Meng et al., 2019, 2020; Wang et al., 2015; Yan et al., 2020; Zhou et al., 2020). Therefore, development of miniaturization and mechanical durability are challenges. (Huang et al., 2020; Zebda et al., 2018).

The recently reported twisted carbon nanotube yarn harvester (twistron harvester), which electrochemically converts stretching mechanical energy into electrical energy, provides 250 W/kg of electrical power in 0.1 M HCl (Kim et al., 2017). When the carbon nanotube yarn is

stretched in the electrolyte, its volume is changed, which consequently induces a capacitance change due to ion movements in the yarn (Kim et al., 2017). As a consequence, electrical energy is induced by the potential change owing to the capacitance change. The twistron harvesters operate in a variety of environments, including electrolytes that contain ions such as sea water, and have a small diameter and no need for an external bias potential. These yarn- or fiber-type energy harvesters are useful for flexible, stretchable, and textile applications. Therefore, this tiny and high-powered twistron harvester offers advantages for fabricating alternatives to batteries in implanted devices.

Although the electrical harvesting properties of the twistron harvester are noteworthy, there are dramatic decreases in performance in the biofluid environment due to the variation in the permeated ions according to the type and size of the physiological ions (Yun et al., 2019; Zhou et al., 2017). The electrical characteristics such as potential of zero charge (PZC) change depending on the electrolyte components. In addition, if the size of the ions is large, it will be difficult to penetrate the twisted yarn, which cause to decrease the energy harvesting performance (Jang et al., 2019). For this reason, in order to be used as a battery substitute in implanted devices, it is necessary to improve the

\* Corresponding author.

E-mail address: [sjk@hanyang.ac.kr](mailto:sjk@hanyang.ac.kr) (S.J. Kim).

<https://doi.org/10.1016/j.bios.2020.112318>

Received 15 January 2020; Received in revised form 19 May 2020; Accepted 20 May 2020

Available online 22 May 2020

0956-5663/© 2020 Elsevier B.V. All rights reserved.

performance of electrical harvesters in biofluid environments.

Here, we describe the enhanced energy harvesting performance of multi-walled carbon nanotube (MWNT) yarn bistructured with ferritin without an external voltage. To increase the energy harvesting performance, there are two methods that can 1) increase capacitance change and 2) the chemical potential difference in the electrochemical system. Ferritin has been reported to have both electrical properties and biocompatibility (Sim et al., 2018; Watt et al., 2012). After bistructuring with ferritin, the capacitance of the harvester is increased 83.2% and the PZC is shifted from 180 to 425 mV because of the electrostatic force of the positively charged ferritin (Sim et al., 2018). The ferritin/MWNT energy harvester improved the peak power by 1.5-fold compared with that of bare MWNT in phosphate-buffered saline (PBS), and it increased the performance in other biofluid solutions (serum and Hank's balanced salt solution (HBSS)). The enhanced energy harvester has a potential to be applied for implant devices due to its small size, stability, and mechanical durability.

## 2. Experimental section

### 2.1. Materials

The MWNT forest, which was fabricated by a previously described method, was provided by Lintec (USA) (Foroughi et al., 2011; Zhang et al., 2005). The ferritin, PBS buffer (10 mM Na<sub>2</sub>HPO<sub>4</sub>, 137 mM NaCl, 2.7 mM KCl, 1.8 mM KH<sub>2</sub>PO<sub>4</sub>) (pH 7.4), and HBSS (138 mM NaCl, 5 mM KCl, 0.3 mM Na<sub>2</sub>HPO<sub>4</sub>, 0.4 mM KH<sub>2</sub>PO<sub>4</sub>, 4 mM NaHCO<sub>3</sub>, 6 mM D-Glucose) (pH 7.4) were purchased from Sigma-Aldrich (USA). Serum (horse serum) were purchased from Invitrogen (USA).

### 2.2. Fabrication of coiled MWNT and ferritin/MWNT yarn

The coiled MWNT yarn was fabricated from a drawable MWNT forest. First, the MWNT sheets, which were drawn with dimensions of 1.5 cm × 15 cm, were stacked in 10 layers on the glass slide. Then, the MWNT sheet rolled into a cylindrical structure. Using a twisting machine, we twisted the cylindrical MWNT sheets (cone spinning method) until the coiled structure was under 10 MPa of stress (Kim et al., 2017). In the case of ferritin/MWNT, the ferritin was sprayed between the 10 layers of MWNT sheets with spacings of 3-4 layers and dried thoroughly at room temperature. After drying, we twisted the ferritin/MWNT sheet until the coiled structure was under 10 MPa of stress. Finally, both the coiled MWNT yarn and ferritin/MWNT yarn were placed in a beaker, following the procedure described in the previous report (Kim et al., 2017).

### 2.3. Characterization

The scanning electron microscope (SEM) images of the coiled MWNT and ferritin/MWNT yarn were obtained with a Hitachi S4700 (Japan). The transmission electron microscopy (TEM) images and energy-dispersive X-ray spectroscopy (EDX) images were obtained with a JEM-2010 (Japan). All the electrochemical measurements were obtained with a Gamry instrument (model: reference 3000). The traces of OCV, cyclic voltammetry (CV) (scan rate: 50 mV/s), and piezo-electroscopy (PECS) (scan rate: 5 mV/s) were collected using a 3-electrode system, and short-circuit current (SCC) was performed with a 2-electrode system.

## 3. Results and discussion

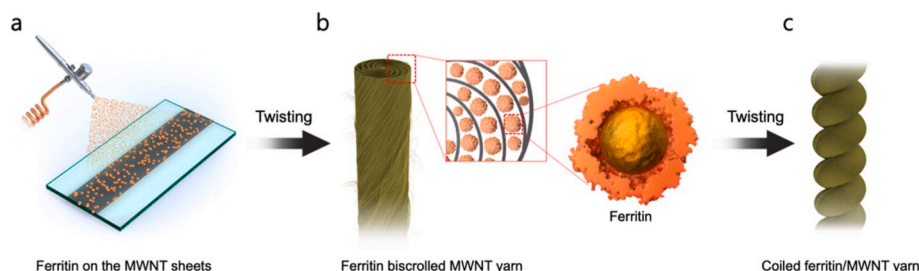
### 3.1. Characterization of the ferritin bistructured MWNT yarn electrode

The ferritin/MWNT yarn was fabricated by spraying ferritin dispersed in water between the MWNT sheets and twisting it until it formed a coiled structure. The details of the fabrication method are

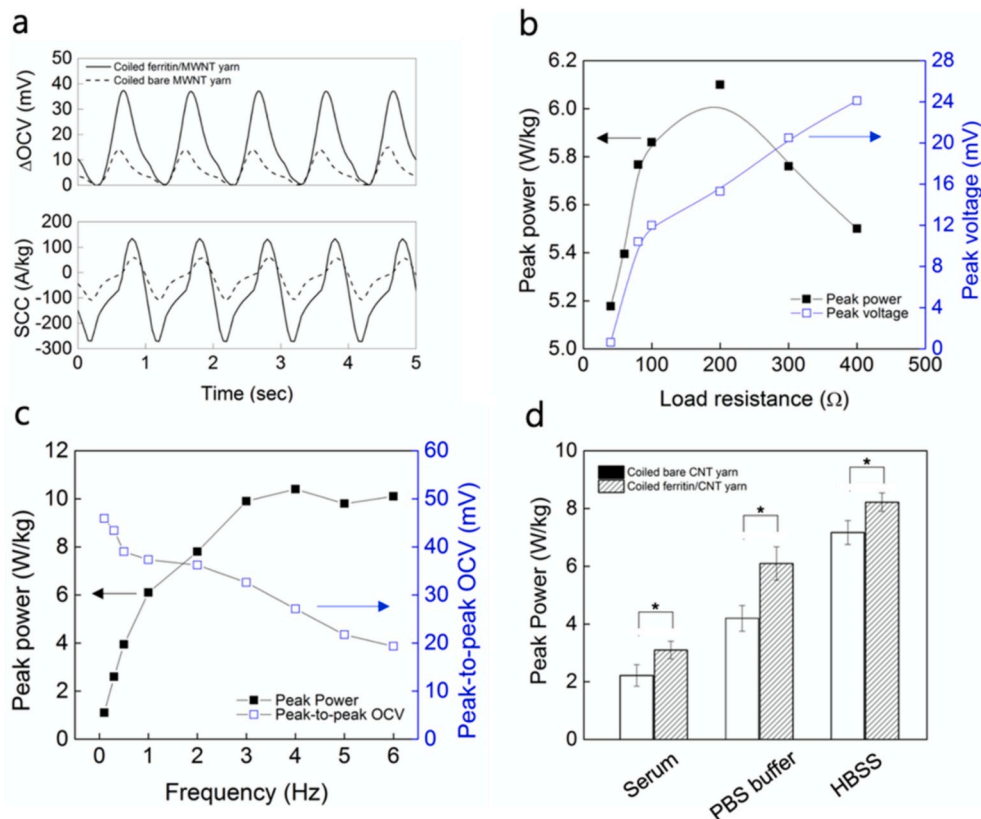
described in the experimental section. Fig. 1a shows the ferritin sprayed on the MWNT stacked sheets, which were drawn from MWNT forest. Ferritin is a globular protein, with a typical inner diameter of 8 nm and an outer diameter of 12 nm (Jin et al., 2019). As shown in the TEM image (Fig. S1), ferritins were attached to the MWNT bundles because it has a natural affinity for carbon nanotubes (Lee et al., 2008; Lin et al., 2004). Moreover, Fe atoms, which are contained in ferritin, were detected on the MWNT sheet by EDX (Fig. S1). The loading weight of the ferritin was controlled by the concentration of the aqueous dispersed solution. The bistructured method of modifying the MWNT sheet, previously reported by Lima et al. (2011) enables twist-based spinning of the yarn from various powders while maintaining guest functionality (Choi et al., 2016; Lima et al., 2011). By bistructuring ferritin, the yarn diameter was increased 7% compared to that of bare MWNT yarn (Fig. S2). The ferritin-sprayed MWNT sheet was then formed into a yarn structure (Fig. 1b, Fig. S3) by twisting 6454.7 turns/m and applying continuous twisting until the coiled structure was under 10 MPa of stress (Fig. 1c). To electrochemically characterize the yarns, the electrochemical cell was composed of the working electrode, a reference electrode, and a counter electrode in the electrolyte (Fig. S4) (Kim et al., 2017). Finally, the performance of the coiled ferritin/MWNT yarn as an electrical energy harvester was measured by stretching and releasing.

### 3.2. Electrical energy harvesting for the coiled ferritin/MWNT yarn harvester

The electrochemical measurements for the MWNT harvester were collected using a potentiostat. All of the electrochemical characterizations involved 40.1 wt% ferritin bistructured MWNT coiling yarn in 0.01 M PBS buffer, which is frequently used as a biological fluid (Lewis et al., 2005; Vidal and Muñoz, 2008). Fig. 2a shows the time dependence of the open-circuit voltage (OCV) and short-circuit current (SCC) of the coiled ferritin/MWNT and bare MWNT yarn at 1 Hz and maximum 30% sinusoidal stretching in 0.01 M PBS buffer. The OCV depending on the strain is shown in Fig. S5. Fig. S6 shows the results for mechanical durability and stability in the electrolyte. The ferritin/MWNT yarn maintained 98% after 3000 cycles (Fig. S6a). Also, peak-to-peak OCV values were retained 91% after 2 weeks (Fig. S6b). The peak-to-peak OCV (37 mV) and peak SCC (135 A/kg) of ferritin/MWNT yarn are 2.8-fold higher than those of bare MWNT yarn. In HCl, the coiled bare MWNT yarn showed a peak-to-peak OCV of 94 mV (Fig. S7). Fig. 2b shows the peak power for energy harvesting at 1 Hz for impedance matching. The maximum peak power is 6.1 W/kg at a load resistance of 200 Ω. In the case of bare MWNT yarn, the peak power was 4.2 W/kg and was matched at 180 Ω (Fig. S8). The energy conversion efficiency was 0.07% when calculated by tensile mechanical energy input and electric energy output during cycling to 30% strain at 1 Hz (Fig. S9). As the frequency of an applied strain gradually increased, peak power increased and eventually plateaued at about 4 Hz because the yarn harvester is limited by its electrical impedance, wherein the peak power was 10.4 W/kg (Fig. 2c) (Kim et al., 2017). When comparing gravimetric peak power of other energy harvesters that is mentioned in bio-environmental applications, our ferritin/MWNT harvester is higher peak power than previously reported harvesters (Table S1) (Cho et al., 2014; Bai et al., 2013; Hu et al., 2011; Hwang et al., 2016; Jang et al., 2019; Jeong et al., 2014; Kim et al., 2013, 2017; Mun et al., 2020; Sharpes et al., 2015; Wu et al., 2014; Zeng et al., 2014, 2016; Zhang et al., 2014; Zhong et al., 2013). The decrease in the peak-to-peak OCV with increasing frequency occurs because the ions cannot match the speed of mechanical deformation (Wee et al., 2010). Fig. 2d shows the peak power for the ferritin/MWNT and bare MWNT yarn in different biofluid electrolytes: HBSS (pH 7.4), PBS buffer (pH 7.4), and serum. The peak power of the ferritin/MWNT yarn was 8.2, 6.1, and 3.1 W/kg in HBSS, PBS buffer, and serum, respectively. For bare MWNT yarn, the peak power was 7.2, 4.2, and 2.3 W/kg in Hank's balanced salt solution (HBSS), PBS buffer, and serum, respectively.



**Fig. 1.** Fabrication process for the harvester electrode. **a)** Schematic image of the ferritin spray coating on the MWNT sheet. **b)** Schematic images of the ferritin biscored MWNT yarn and cross section of ferritin/MWNT yarn and ferritin. **c)** Coiled structure of the ferritin/MWNT yarn.

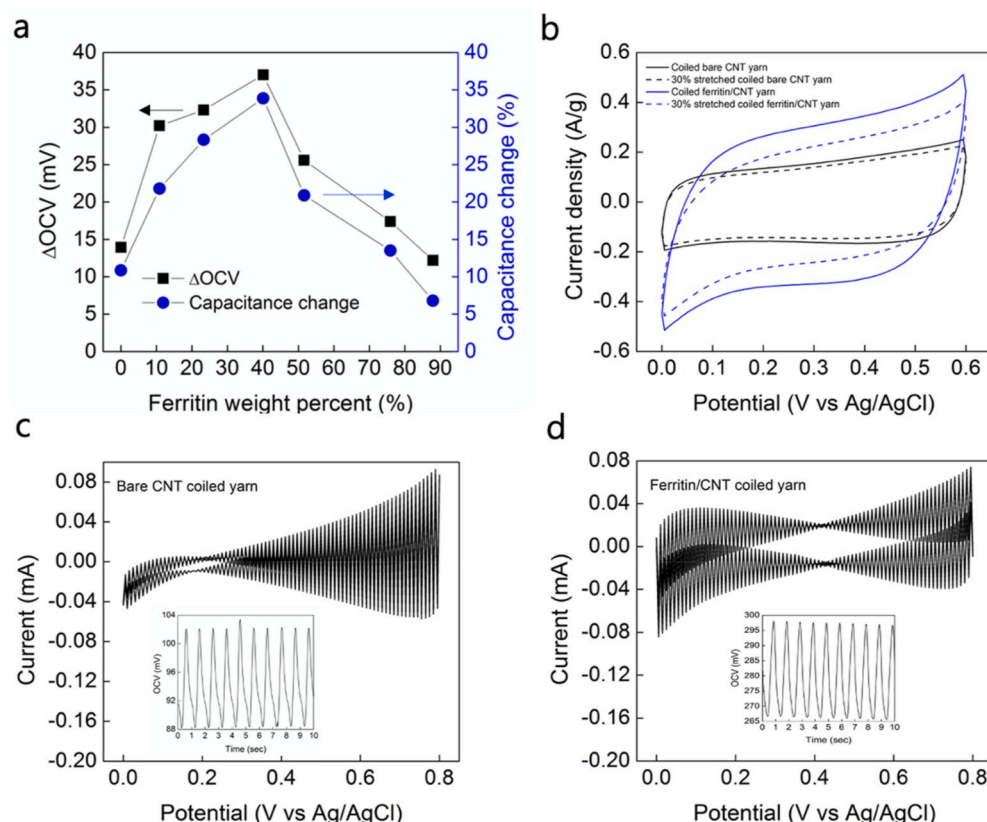


**Fig. 2.** Electrical energy harvesting performance of the coiled ferritin/MWNT yarn. **a)** Results of open-circuit voltage (OCV) and short-circuit current (SCC) during applied sinusoidal 30% stretching in the PBS buffer solution. **b)** Generated peak power and peak voltage versus load resistance for coiled ferritin/CNT yarn. **c)** Frequency dependence of peak-to-peak OCV and peak power (sinusoidal stretching: 30%, electrolyte: PBS buffer solution). **d)** Comparison of peak power for coiled bare MWNT yarn and ferritin/MWNT yarn in the different biofluid electrolytes (sinusoidal stretching: 30%). Error bars represent standard deviation. Statistical significance was accepted for  $p$ -values  $< 0.05$  (\*).

### 3.3. Electrochemical characterization for the coiled ferritin/MWNT yarn harvester

Fig. 3 shows the electrochemical characteristics of ferritin biscored MWNT yarn and the reasons for the improved performance. Fig. 3a shows the peak-to-peak of OCV and capacitance change according to the ferritin loading weight percent in the coiled MWNT yarn for 30% stretching. The highest peak-to-peak OCV (37 mV) was observed at 40 wt%, decreasing dramatically after increasing the ferritin loading weight. The cyclic voltammetry (CV) curves for 0% and 30% stretching of coiled MWNT yarn and 40 wt% biscored ferritin/MWNT yarn are compared in Fig. 3b. The CV curves indicate electrochemical double-layer charging (EDLC) capacitance and pseudocapacitance of the MWNT and ferritin, respectively (Kim et al., 2005). The capacitances of the 0% stretched bare MWNT and ferritin/MWNT yarn were 1.5 mF/g and 2.8 mF/g, respectively. The capacitance enhancement of the ferritin/MWNT yarn was caused by a combination of the EDLC capacitance of the MWNT and pseudocapacitance of the ferritin. The contribution to the capacitance by double-layer capacitive process were above 86% (Fig. S10) (Huang et al., 2017; Zhou et al., 2019). Although ferritin

contains an iron ion which is known to exhibit a redox reaction, the ferritin/MWNT yarns are highly capacitive at potential between 0 to 0.6 V vs Ag/AgCl in PBS solution. After 30% stretching, capacitance of the bare MWNT and ferritin/MWNT yarn decreased 10.8% and 25.3%, respectively. Fig. 3c and d shows piezoelectroscopy (PECS) for the characterized potential of zero charge (PZC) for each harvester. The PECS method was utilized according to previous reports for measuring PZC using CV during stretching of the harvester (Kim et al., 2017). Determining the PZC of the harvester is necessary for evaluating the equilibrium charge state because energy harvesting can occur by generating an equilibrium charge on the electrode. From the PECS measurements, the PZC is where the ac current is minimized, and the current phase is reversed. Accordingly, the PZC of coiled MWNT yarn is observed at 180 mV in 0.01 M PBS buffer solution (pH 7.4) (Fig. 3c). In the case of the coiled ferritin(40 wt%)/MWNT yarn, PZC is shifted from 180 mV to 430 mV owing to the positively charged ferritin. The baseline of the OCV and PZC by ferritin concentrations are shown in Fig. S11. In these harvesters, the difference between the baseline of the OCV and the PZC is the intrinsic bias potential. Consequently, one of the reasons why the ferritin/MWNT yarn energy harvester performance is higher than



**Fig. 3. Electrochemical characterization of coiled ferritin/MWNT yarn.** a) Dependence of the peak-to-peak OCV (1 Hz sinusoidal 30% stretching) and capacitance change, after 30% stretching, on ferritin weight percent. b) Cyclic voltammetry (CV) curves (at 50 mV/s scan rate) for 0% and 30% stretched of the coiled bare MWNT and ferritin/MWNT yarn. Piezoelectrochemical spectroscopy of c) bare coiled MWNT yarn and d) ferritin/MWNT coiled yarn (at 5 mV/s scan rate, and 1 Hz of the sinusoidal stretching). Inset showing OCV during applied sinusoidal 30% stretching. All samples were measured in 0.01 M PBS buffer solution (pH 7.4).

that of bare MWNT yarn is that the difference between the baseline of OCV and PZC is 133 mV, which is larger than that of 83 mV of bare MWNT yarn. Additionally, it was found that OCV-PZC is higher in both serum and HBSS (Table S2). As a result, the performance improvement from biscrolling ferritin in the MWNT is due to the increase in the capacitance change and the baseline of OCV-PZC according to formula  $Q = CV$  (where  $Q$  is the charge,  $C$  is the capacitance, and  $V$  is the voltage) (Kim et al., 2017).

#### 4. Conclusion

In conclusion, the present study showed that the biscrolled ferritins improve the energy harvesting performance of a coiled MWNT yarn in biological condition. The coiled ferritin/MWNT yarn loaded 40.1 wt% of ferritin shows a 2.8-fold higher peak-to-peak OCV and a 1.5-fold higher peak power than those of the bare MWNT yarn. This improved electrical performance resulted from the increased capacitance change and the shifted PZC owing to the positively charged ferritin when stretched. Therefore, it suggests that the improved performance increase the potential to expand the applicability of the energy harvesting technology of MWNT yarn in a biological environment. However, further studies are warranted to improve the power and/or to connect MWNT yarns in series/parallel for practical application to implantable device.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### CRediT authorship contribution statement

**Hyunsoo Kim:** Conceptualization, Methodology, Investigation, Writing - original draft, Visualization. **Jong Woo Park:** Formal analysis,

Methodology. **Jaе Sang Hyeon:** Formal analysis, Methodology. **Hyeon Jun Sim:** Formal analysis, Methodology. **Yongwoo Jang:** Methodology, Writing - review & editing. **Yujin Shim:** Visualization, Methodology. **Chi Huynh:** Resources, Methodology. **Ray H. Baughman:** Resources, Conceptualization. **Seon Jeong Kim:** Supervision, Project administration, Conceptualization.

#### Acknowledgements

This work was supported by the Creative Research Initiative Center for Self-powered Actuation in National Research Foundation of Korea. Support at the University of Texas at Dallas was provided by Air Force Office of Scientific Research grants FA9550-18-1-0510, DARPA grant HR00119C0042, and Robert A. Welch Foundation grant AT-0029. The spinnable MWNT forests were provided by LINTEC OF AMERICA, INC.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.bios.2020.112318>.

#### References

- Bai, P., Zhu, G., Lin, Z.-H., Jing, Q., Chen, J., Zhang, G., Ma, J., Wang, Z.L., 2013. *ACS Nano* 7, 3713–3719.
- Chen, J., Huang, Y., Zhang, N., Zou, H., Liu, R., Tao, C., Fan, Xing, Wang, Z.L., 2016. *Nat. Energy* 1, 16138.
- Chen, G., Li, Y., Bick, M., Chen, J., 2020. *Chem. Rev.* 120, 3668–3720.
- Chen, J., Wang, Z.L., 2017. *Joule* 1, 480–521.
- Choi, C., Kim, K.M., Kim, K.J., Lepro, X., Spinks, G.M., Baughman, R.H., Kim, S.J., 2016. *Nat. Commun.* 7, 13811.
- Cho, K.-H., Park, H.-Y., Heo, J.S., Priya, S., 2014. *J. Appl. Phys.* 115, 204108.
- Cottrill, A.L., Liu, A.T., Kunai, Y., Koman, V.B., Kaplan, A., Mahajan, S.G., Liu, P.W., Toland, A.R., Strano, M.S., 2018. *Nat. Commun.* 9, 664.
- Dong, K., Wang, Y.-C., Deng, J., Dai, Y., Zhang, S.L., Zou, H., Gu, B., Sun, B., Wang, Z.L., 2017. *ACS Nano* 11, 9490–9499.

- Foroughi, J., Spinks, G.M., Wallace, G.G., Oh, J., Kozlov, M.E., Fang, S.L., Mirfakhrai, T., Madden, J.D.W., Shin, M.K., Kim, S.J., Baughman, R.H., 2011. *Science* 334, 494–497.
- Guo, H.Y., Wen, Z., Zi, Y.L., Yeh, M.H., Wang, J., Zhu, L.P., Hu, C.G., Wang, Z.L., 2016. *Adv. Energy Mater.* 6, 1501593.
- Han, M.D., Wang, H.L., Yang, Y.Y., Liang, C.M., Bai, W.B., Yan, Z., Li, H.B., Xue, Y.G., Wang, X.L., Akar, B., Zhao, H.B., Luan, H.W., Lim, J., Kandela, I., Ameer, G.A., Zhang, Y.H., Huang, Y.G., Rogers, J.A., 2019. *Nat. Electron* 2, 26–35.
- Hinchet, R., Yoon, H.J., Ryu, H., Kim, M.K., Choi, E.K., Kim, D.S., Kim, S.W., 2019. *Science* 365, 491–494.
- Huang, X., Wang, L., Wang, H., Zhang, B., Wang, X., Stening, R.Y.Z., Sheng, X., Yin, X.L., 2020. *Small* 16, 1902827.
- Hu, Y., Xu, C., Zhang, Y., Lin, L., Snyder, R.L., Wang, Z.L., 2011. *Adv. Mater.* 23, 4068–4071.
- Huang, Z.-H., Liu, T.-Y., Song, Y., Li, Y., Liu, X.-X., 2017. *Nanoscale* 9, 13119–13127.
- Hwang, G.T., Annappureddy, V., Han, J.H., Joe, D.J., Baek, C., Park, D.Y., Kim, D.H., Park, J.H., Jeong, C.K., Park, K.-I., Choi, J.-J., Kim, D.K., Ryu, J., Lee, K.J., 2016. *Adv. Energy Mater.* 6, 1600237.
- Jang, Y., Kim, S.M., Kim, K.J., Sim, H.J., Kim, B.J., Park, J.W., Baughman, R.H., Ruhparwar, A., Kim, S.J., 2019. *ACS Sens.* 4, 2893–2899.
- Jeong, C.K., Park, K.I., Ryu, J., Hwang, G.T., Lee, K.J., 2014. *Adv. Funct. Mater.* 24, 2620–2629.
- Jin, Y., He, J., Fan, K., Yan, X., 2019. *Nanoscale* 11, 12449–12459.
- Kim, K.-B., Kim, C.-I., Jeong, Y.H., Lee, Y.-J., Cho, J.-H., Paik, J.-H., Nahm, S., 2013. *J. Eur. Ceram. Soc.* 33, 305–311.
- Kim, S.H., Haines, C.S., Li, N., Kim, K.J., Mun, T.J., Choi, C., Di, J.T., Oh, Y.J., Oviedo, J. P., Bykova, J., Fang, S.L., Jiang, N., Liu, Z.F., Wang, R., Kumar, P., Qiao, R., Priya, S., Cho, K., Kim, M., Lucas, M.S., Drummy, L.F., Maruyama, B., Lee, D.Y., Lepro, X., Gao, E.L., Albarq, D., Ovalle-Robles, R., Kim, S.J., Baughman, R.H., 2017. *Science* 357, 773–778.
- Kim, Y.-T., Ito, Y., Tadai, K., Mitani, T., Kim, U.-S., Kim, H.-S., Cho, B.-W., 2005. *Appl. Phys. Lett.* 87, 234106.
- Lee, J.W., Shin, K.M., Lynam, C., Spinks, G.M., Wallace, G.G., Kim, S.J., 2008. *Smart Mater. Struct.* 17, 045029.
- Lewis, A.C., Kilburn, M.R., Papageorgious, I., Allen, G.C., Case, C.P., 2005. *J. Biomed. Mater. Res.* 73, 456–467.
- Lima, M.D., Fang, S.L., Lepro, X., Lewis, C., Ovalle-Robles, R., Carretero-Gonzalez, J., Castillo-Martinez, E., Kozlov, M.E., Oh, J.Y., Rawat, N., Haines, C.S., Haque, M.H., Aare, V., Stoughton, S., Zakhidov, A.A., Baughman, R.H., 2011. *Science* 331, 51–55.
- Lin, Y., Allard, L.F., Sun, Y.P., 2004. *J. Phys. Chem. B* 108, 3760–3764.
- Meng, K., Chen, J., Li, X., Wu, Y., Fan, W., Zhou, Z., He, Q., Wang, X., Fan, X., Zhang, Y., Yang, J., Wang, Z.L., 2019. *Adv. Funct. Mater.* 29, 1806388.
- Meng, K., Zhao, S., Zhou, Y., Wu, Y., Zhang, S., He, Q., Wang, X., Zhou, Z., Fan, W., Tan, X., Yang, J., Chen, J., 2020. *Matter* 2, 896–907.
- Mun, T.J., Kim, S.H., Park, J.W., Moon, J.H., Jang, W., Huynh, C., Baughman, R.H., Kim, S.J., 2020. *Adv. Funct. Mater.* <https://doi.org/10.1002/adfm.202000411>, 2000411.
- Pu, X., Liu, M., Chen, X., Sun, J., Du, C., Zhang, Y., Zhai, J., Hu, W., Wang, Z.L., 2017. *Sci. Adv.* 3, e1700015.
- Ryu, H., Yoon, H.J., Kim, S.W., 2019. *Adv. Mater.* 31, e180289.
- Sim, H.J., Choi, C., Lee, D.Y., Kim, H., Yun, J.H., Kim, J.M., Kang, T.M., Ovalle, R., Baughman, R.H., Kee, C.W., Kim, S.J., 2018. *Nano Energy* 47, 385–392.
- Sharpes, N., Abdelkefi, A., Priya, S., 2015. *Appl. Phys. Lett.* 107, 093901.
- Vidal, C.V., Muñoz, A.I., 2008. *Corrosion Sci.* 50, 1954–1961.
- Wang, L.Z., Chen, J., Lin, L., 2015. *Energy Environ. Sci.* 8, 2250–2282.
- Watt, G.D., Kim, J.-W., Zhang, B., Miller, T., Harb, J.N., Davis, R.C., Choi, S.H., 2012. *Journal of Nanotechnology* 2012, 516309.
- Wee, G., Larsson, O., Srinivasan, M., Berggren, M., Crispin, X., Mhaisalkar, S., 2010. *Adv. Funct. Mater.* 20, 4344–4350.
- Wu, W., Wang, L., Li, Y., Zhang, F., Lin, L., Niu, S., Chenet, D., Zhang, X., Hao, Y., Heinz, T.F., Hone, J., Wang, Z.L., 2014. *Nature* 514, 470–474.
- Yan, C., Gao, Y., Zhao, S., Zhang, S., Zhou, Y., Deng, W., Li, Z., Jiang, G., Jin, L., Tian, G., Yang, T., Chu, X., Xiong, D., Wang, Z., Li, Y., Yang, W., Chen, J., 2020. *Nano Energy* 67, 104235.
- Yun, T.G., Bae, J., Rothschild, A., Kim, I.-D., 2019. *ACS Nano* 13, 12703–12709.
- Zhou, Y., Hou, Y., Li, Q., Yang, L., Cao, Y., Choi, K.H., Wang, Q., Zhang, Q.M., 2017. *Adv. Mater. Technol.* 2, 1700118.
- Zebda, A., Alcaraz, J.-P., Vadgama, P., Shleev, S., Menteer, S.D., Boucher, F., Cinquin, P., Martin, D.K., 2018. *Bioelectrochemistry* 124, 57–72.
- Zhang, N., Chen, J., Huang, Y., Guo, W., Yang, J., Du, J., Fan, X., Tao, C., 2016. *Adv. Mater.* 28, 263–269.
- Zhang, C., Tang, W., Han, C., Fan, F., Wang, Z.L., 2014. *Adv. Mater.* 26, 3580–3591.
- Zhang, M., Fang, S.L., Zakhidov, A.A., Lee, S.B., Aliev, A.E., Williams, C.D., Atkinson, K. R., Baughman, R.H., 2005. *Science* 309, 1215–1219.
- Zhang, N., Huang, F., Zhao, S., Lv, X., Zhou, Y., Xiang, S., Xu, S., Li, Y., Chen, G., Tao, C., Nie, Y., Chen, J., Fan, X., 2020. *Matter* 2, 1260–1269.
- Zheng, Q., Zhang, H., Shi, B., Xue, X., Liu, Z., Jin, Y., Ma, Y., Zou, Y., Wang, X., An, Z., Tang, W., Zhang, W., Yang, F., Liu, Y., Lang, X., Xu, Z., Li, Z., Wang, Z.L., 2016. *ACS Nano* 10, 6510–6518.
- Zheng, Q., Shi, B., Fan, F., Wang, X., Yan, L., Yuan, W., Wang, S., Liu, H., Li, Z., Wang, Z. L., 2014. *Adv. Mater.* 26, 5851–5856.
- Zhong, J., Zhong, Q., Fan, F., Zhang, Y., Wang, S., Hu, B., Wang, Z.L., Zhou, J., 2013. *Nano Energy* 2, 491–497.
- Zhou, Z., Liu, T., Khan, A.U., Liu, G., 2019. *Sci. Adv.* 5, eaau6852.
- Zhou, Z., Padgett, S., Cai, Z., Conta, G., Wu, Y., He, Q., Zhang, S., Sun, C., Liu, J., Fan, E., Meng, K., Lin, Z., Uy, C., Yang, J., Chen, J., 2020. *Biosens. Bioelectron.* 155, 112064.