Energy harvesting analysis of structural composite utilizing contact electrification and electrostatic induction

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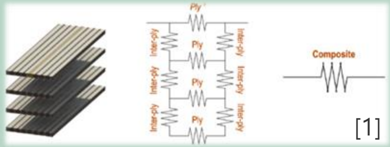
Introduction

● Research background

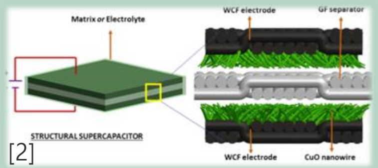
Smart Structural Composite

Functions

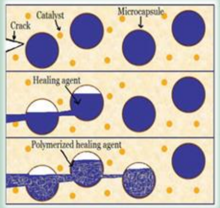
- Light weight & high strength
- Strain sensing


[1]

- Energy storage


[2]

- Self-healing, self-heating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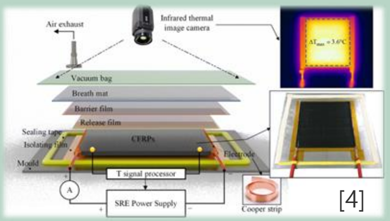
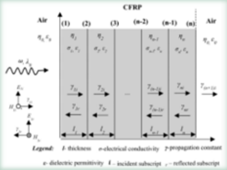
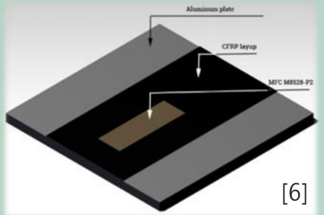

[4]

- Electromagnetic interference (EMI) shielding


[5]

- Energy harvesting


[6]

[1] Hyung Doh Roh, Beom-Gon Cho, In-Yong Lee, Young-Bin Park, Composites Science and Technology, Volume 214, 2021, 108946, ISSN 0266-3538
[2] Biplab K. Deka, Ankita Hazarika, Jisoo Kim, Young-Bin Park, Hyung Wook Park, Composites Part A: Applied Science and Manufacturing, Volume 87, 2016, 256-262, ISSN 1359-835X
[3] Banshiwal, Jeetendra Kumar and Durgesh Nath Tripathi. Functional Materials, 2019
[4] Liu, S., Li, Y., Shen, Y. et al. Int J Adv Manuf Technol, Volume 103, 2019, 3479–3493
[5] Mikinka, E., Siwak, M. J Mater Sci: Mater Electron, Volume 32, 2021, 24585–2464
[6] A. Alsaadi, Yu Shi, Lei Pan, Jie Tao, Yu Jia, Composites Science and Technology, Volume 178, 2019, 1-10, ISSN 0266-3538,

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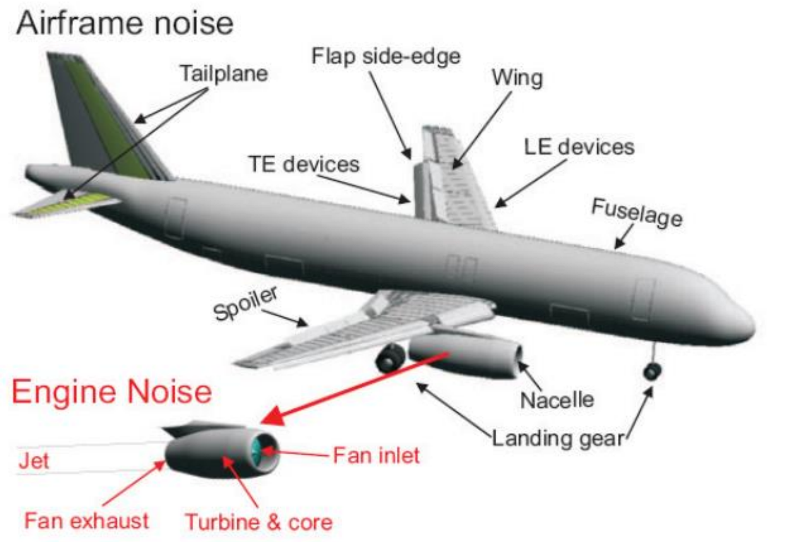
Introduction

Research motivation

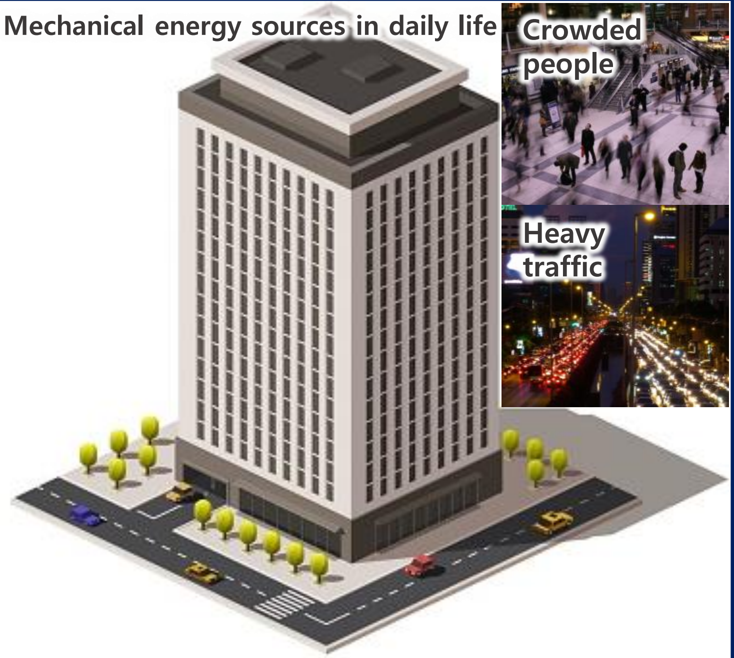
- Need to develop technologies to capture and utilize mechanical energy from structures

Major sources of Airframe and engine noise

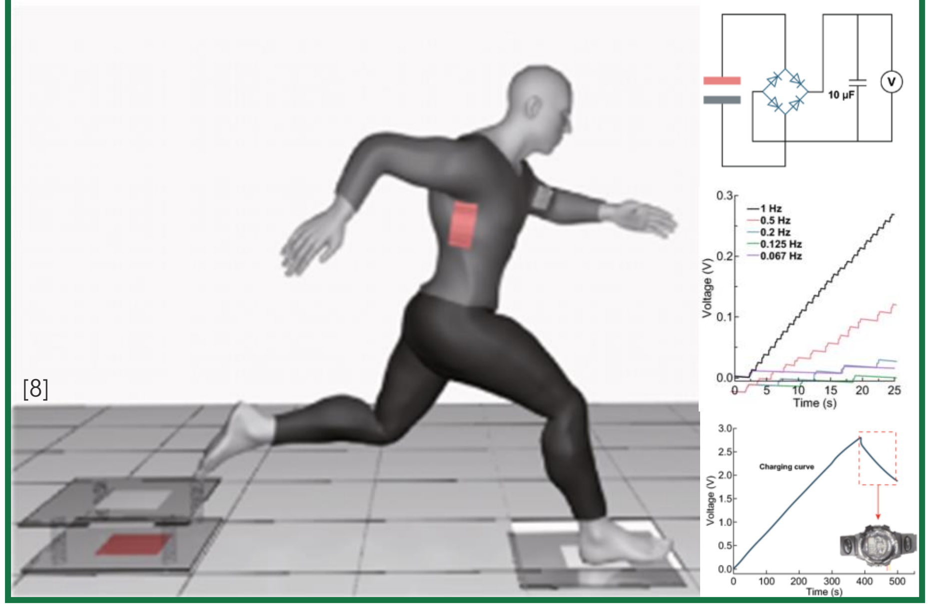


10 ~ 1000 Hz range of vibration [7]

Mechanical energy sources in daily life



Example of research on Triboelectric Nanogenerators (TENGs)



Abundant Mechanical Energy → **Structural Energy Harvester - TENG tile, TENG road..** → Semi-permanent Energy Harvesting

[7] Zhang, X., Yang, Y., & Peng, K. *2013 IEEE 8th Conference on Industrial Electronics and Applications (ICIEA)*, 2013, 617-621.

[8] Ye, C., Dong, S., Ren, J. *et al.* *Nano-Micro Lett.* **12**, 12, 2020.

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Introduction

● Objective

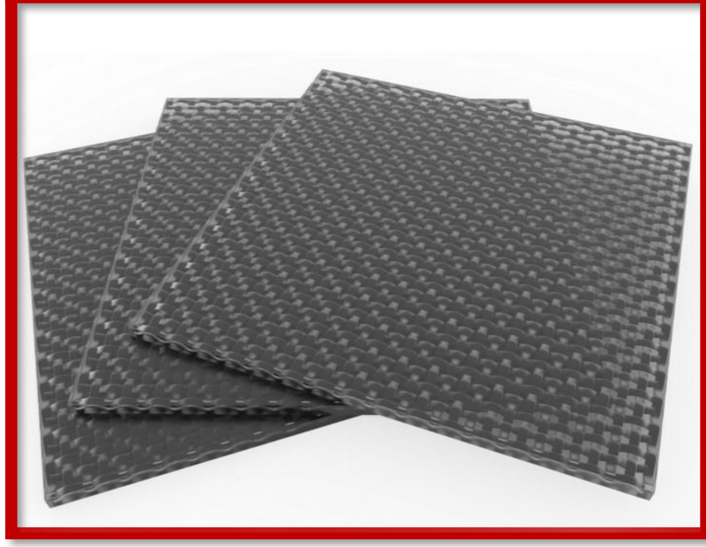
- Inventing self-powering structural composite

- Utilize

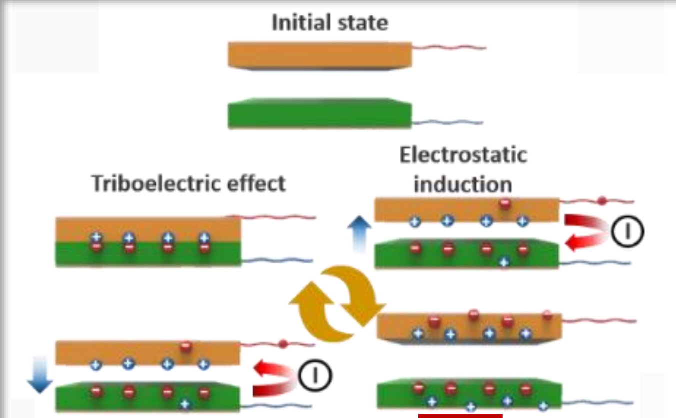
  1) the existing structure of carbon fiber reinforced plastic, which contains both conductive and dielectric materials

  2) a triboelectric nanogenerator mechanism that converts mechanical energy into electrical energy

Carbon-fiber-reinforced Plastic (CFRP)

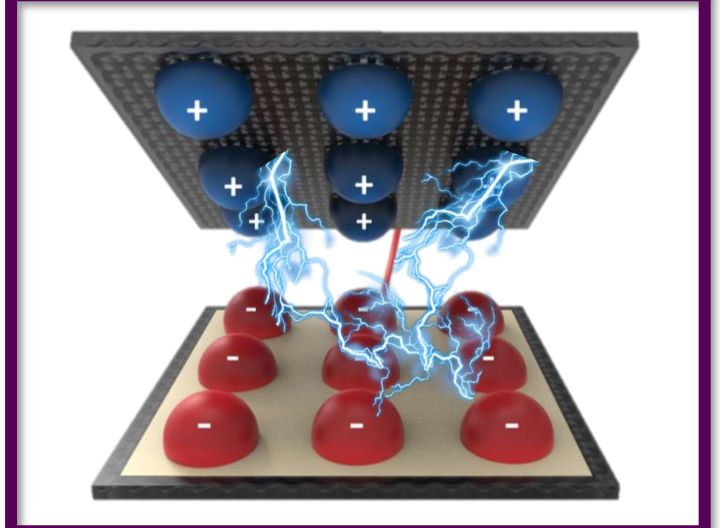


Triboelectric Nanogenerator (TENG)



$$J_D = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \boxed{\frac{\partial \boldsymbol{P}_s}{\partial t}}$$

Structural Energy Harvester

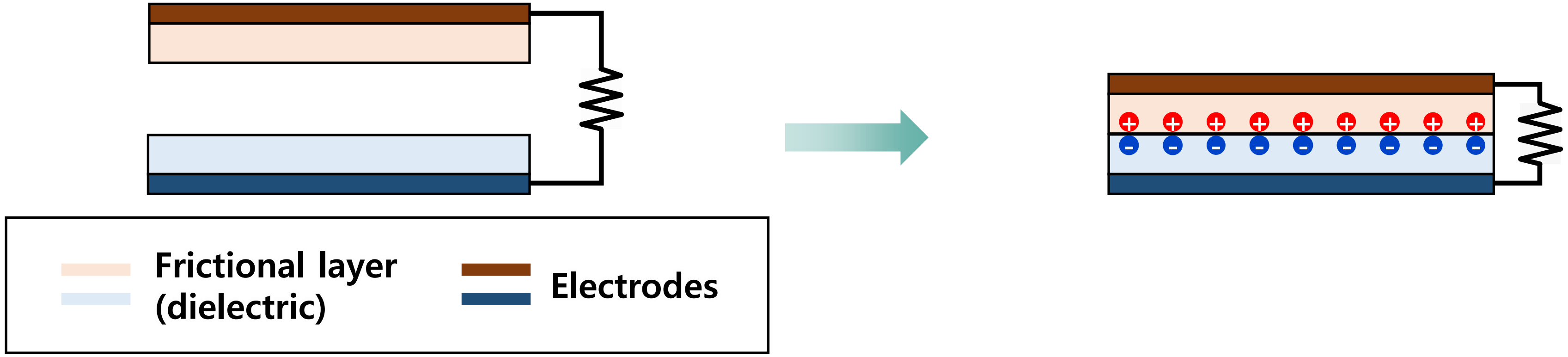


* $\frac{\partial P_s}{\partial t}$: Current generated by a dielectric polarization field created by a static charge on a surface

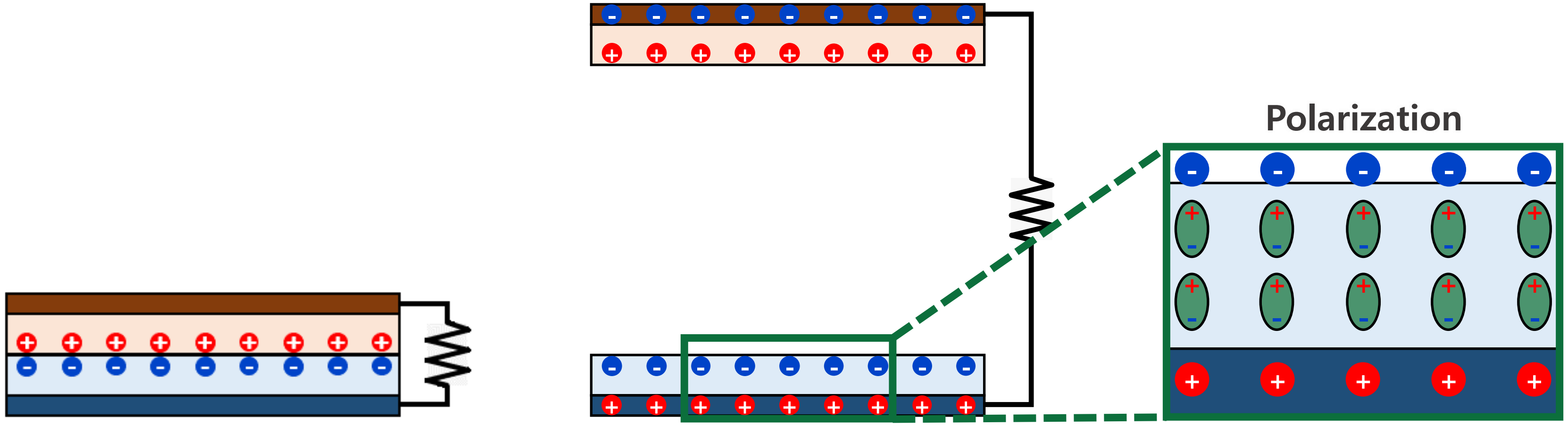
Introduction

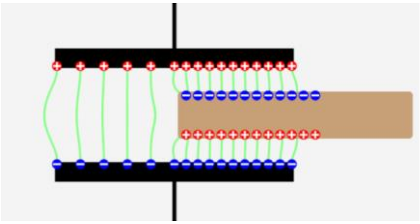
- **Working mechanism of triboelectric nanogenerator (TENG)**

1) Triboelectrification



2) Electrostatic induction



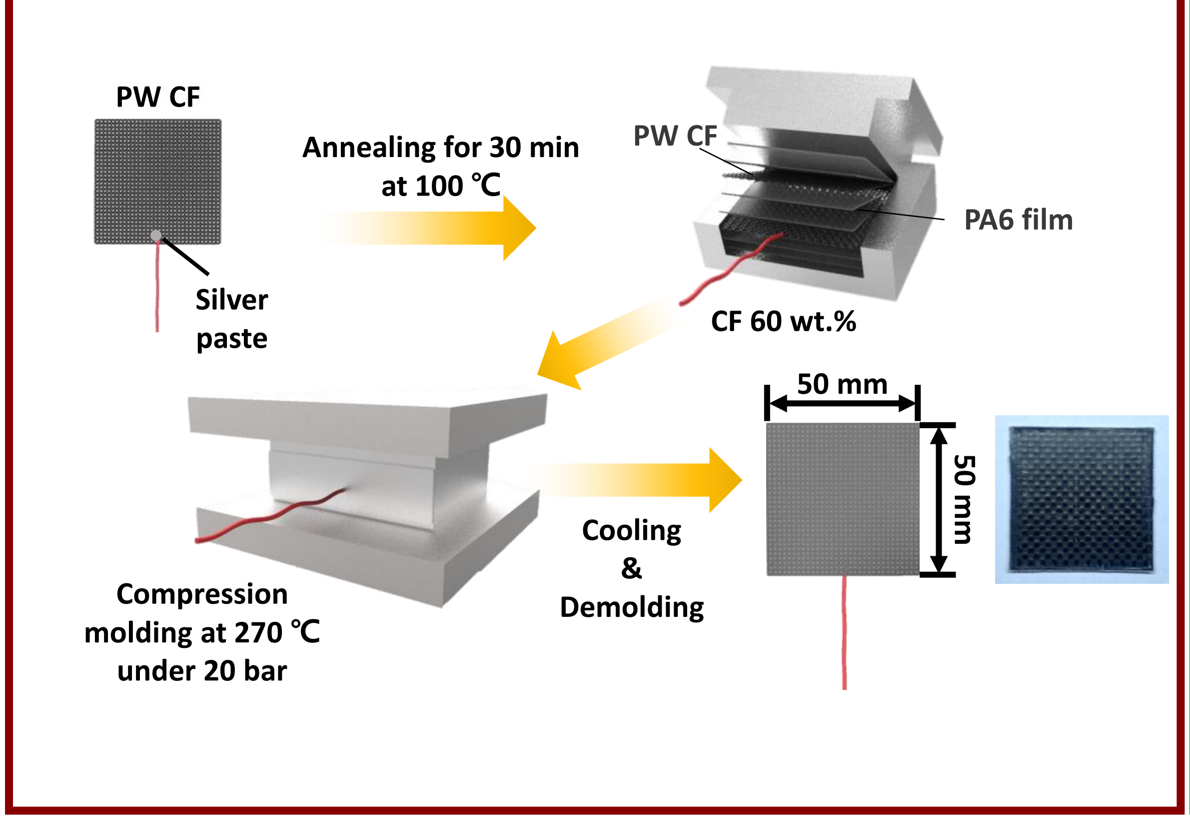


- TENG works with the coupling of triboelectrification and electrostatic induction

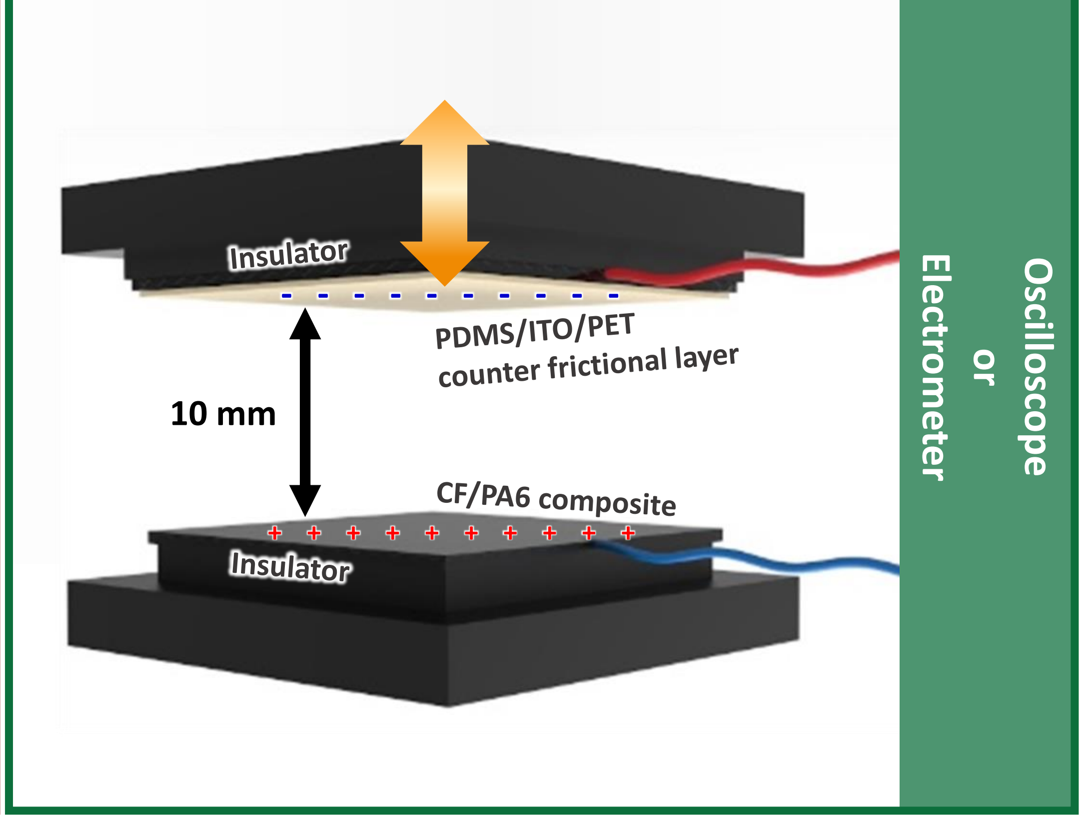
Introduction

- **Fabrication and experimental setup**

▪ **Fabrication process - Heating compression molding**

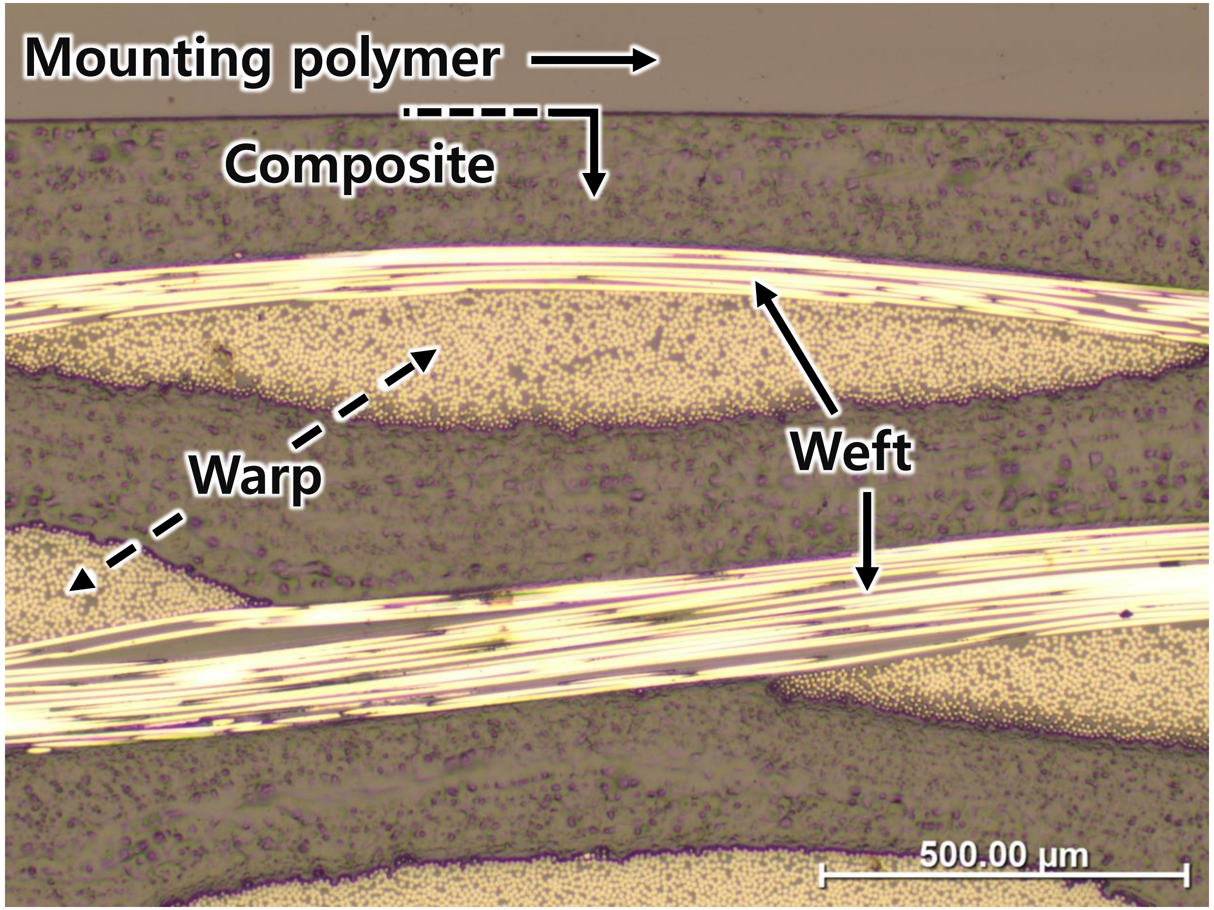


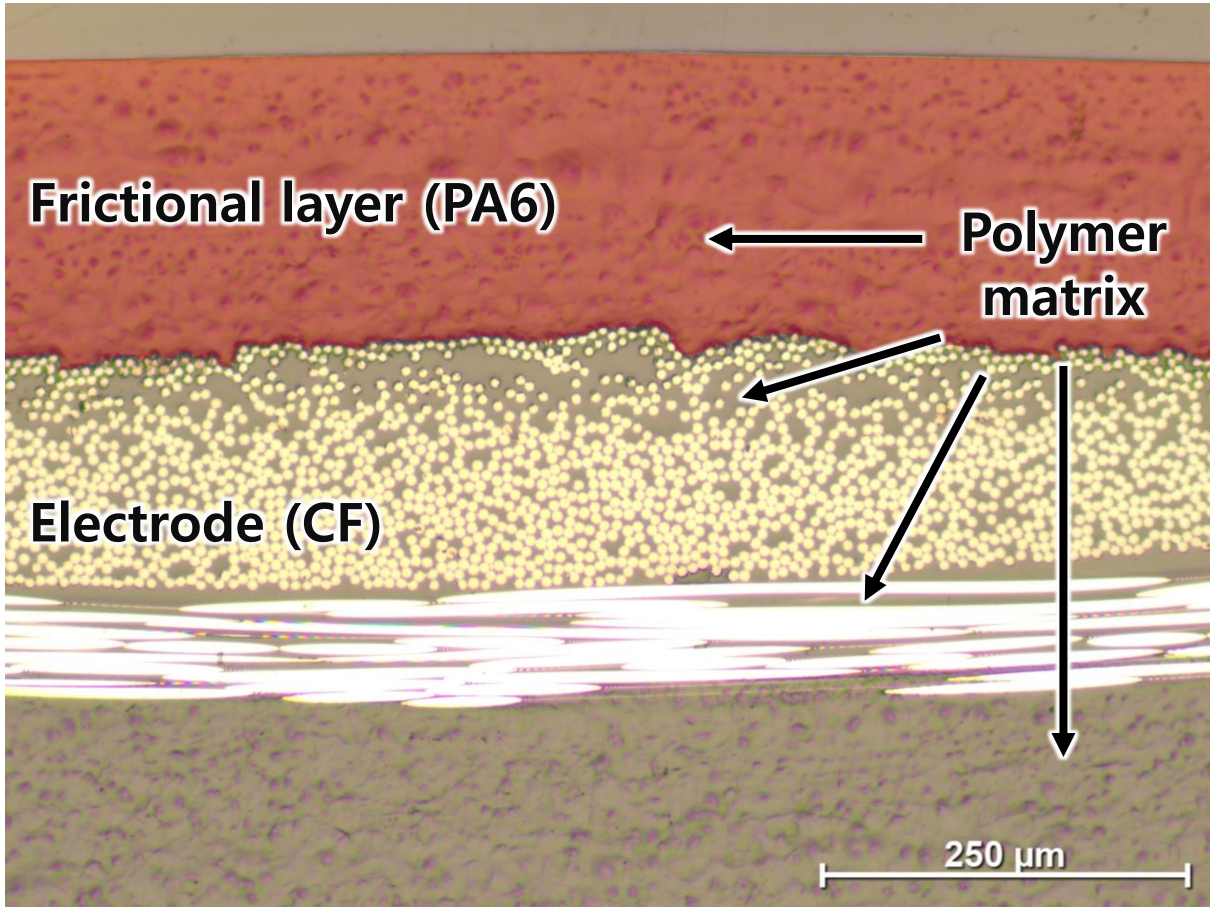
▪ **Experimental setup**



Result

- Optical microscopy image of cross section of PWCF/PA6 composite

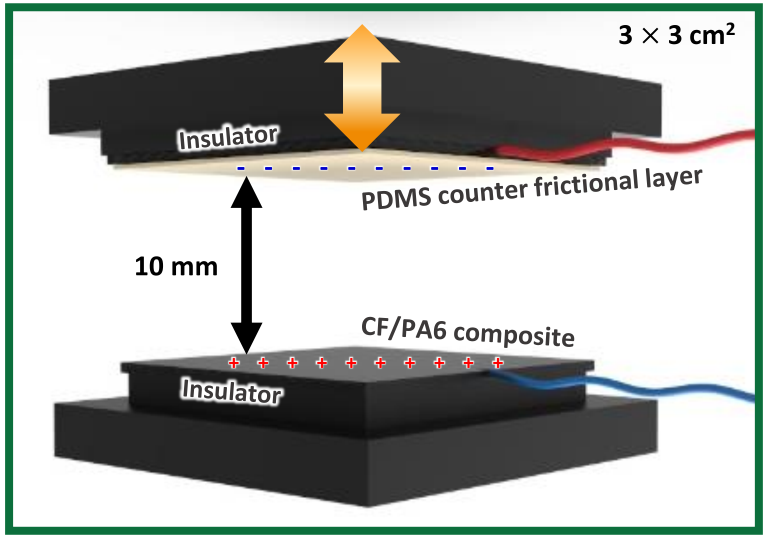


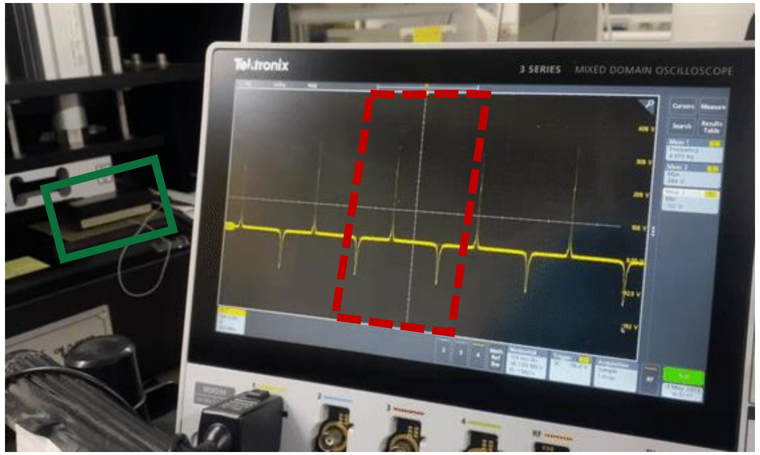


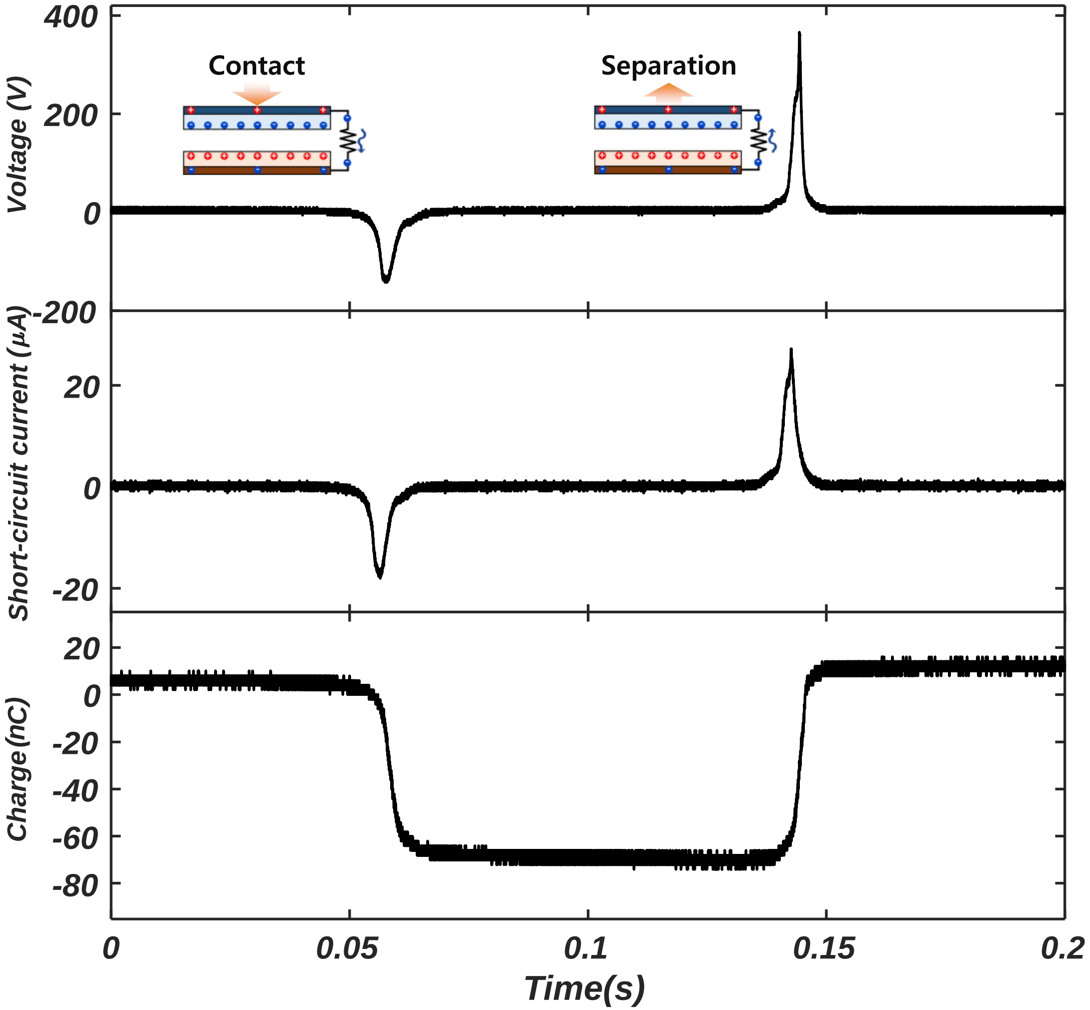
Result

● Energy harvesting performance of carbon fiber/PA6 composite

• Analyzing a single voltage signal





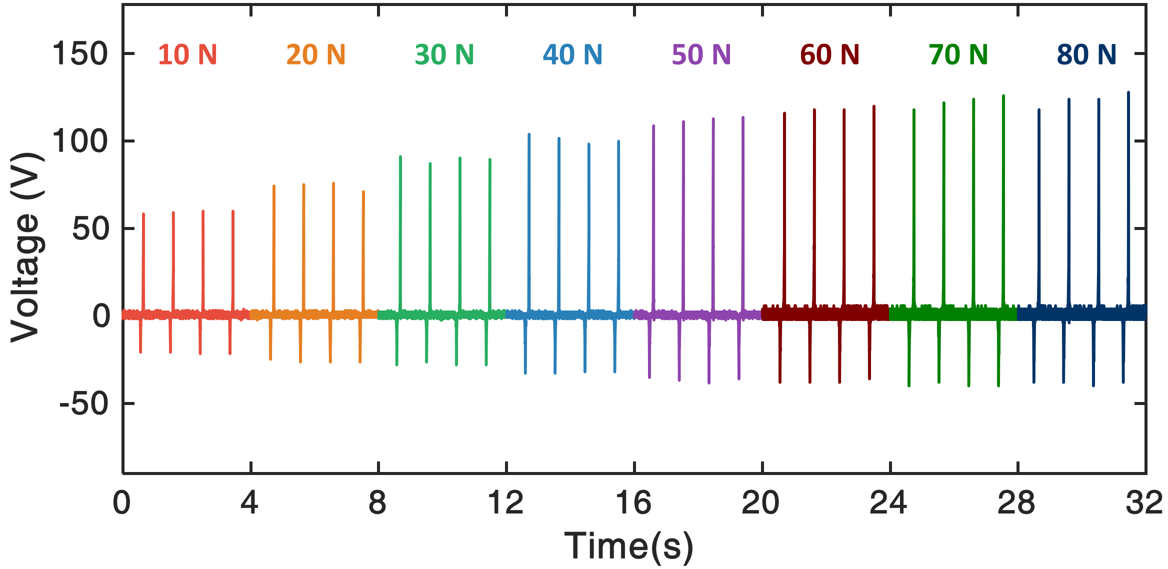


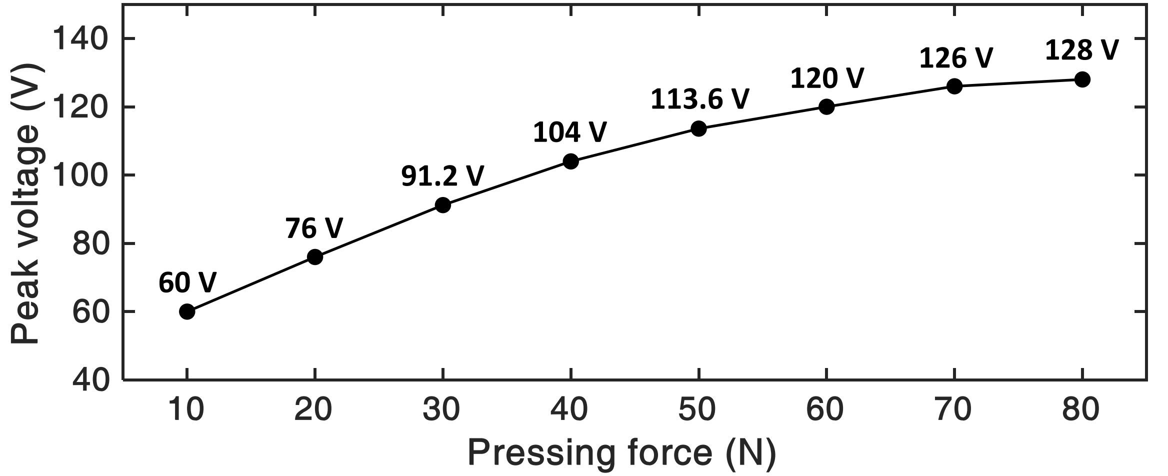
- A negative voltage was generated when they are in contact, and a positive voltage was generated when they are separated.

Result

- Voltage depending on press force

Tapping distance : 10 mm
Frequency : 1 Hz





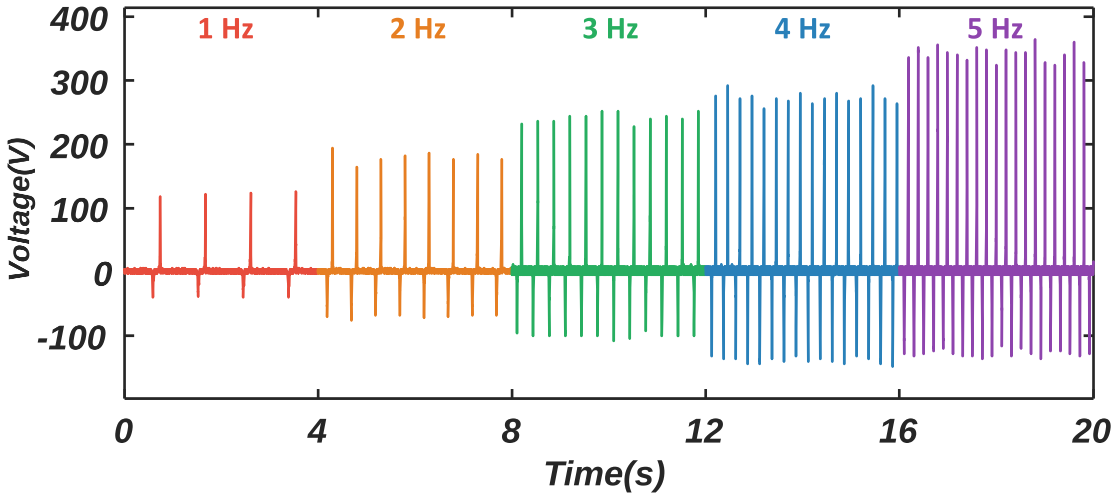
- From 10 N to 80 N, voltage gradually increased.

Result

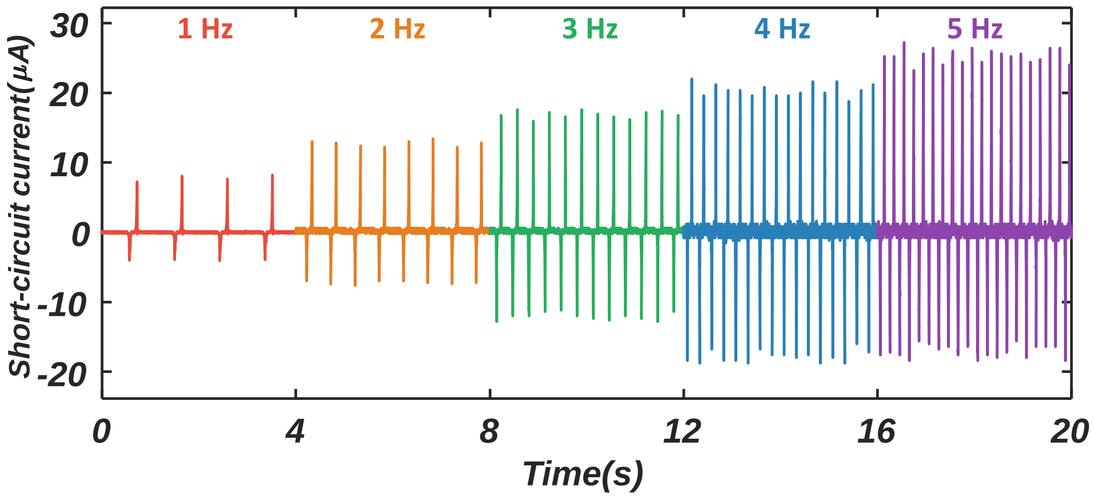
- Voltage, short-circuit current depending on tapping speed

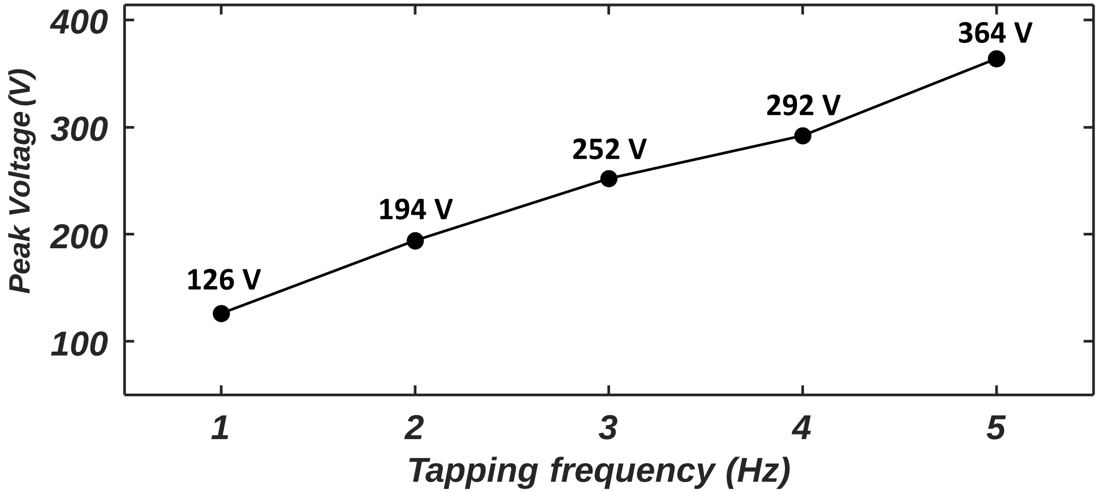
Tapping distance : 10 mm
Pressing force : 70 N

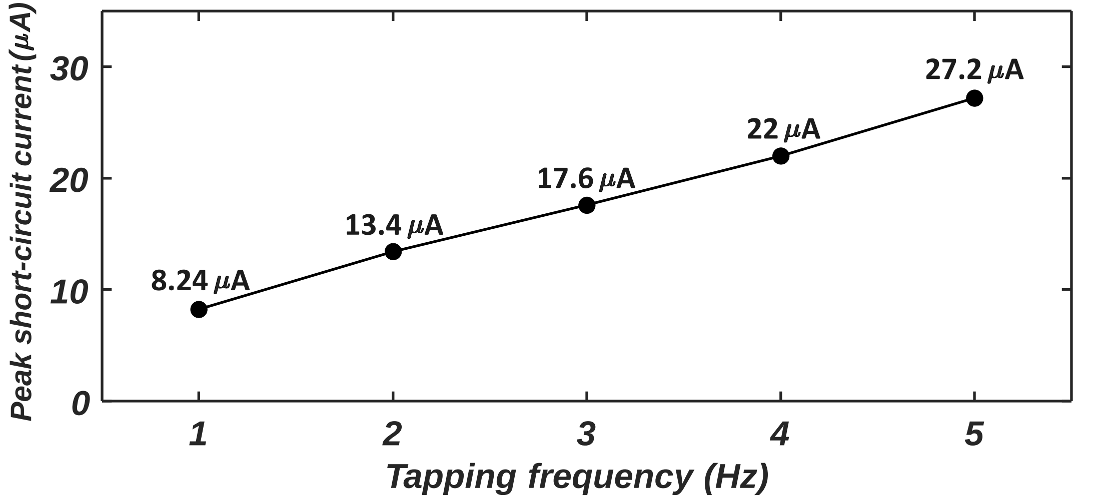
- Voltage



- Short-circuit current





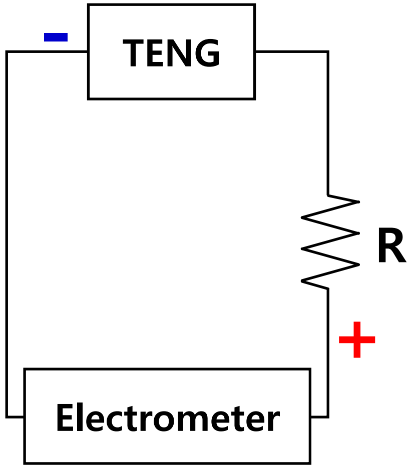


- Voltage and short-circuit current increased as tapping frequency increased.

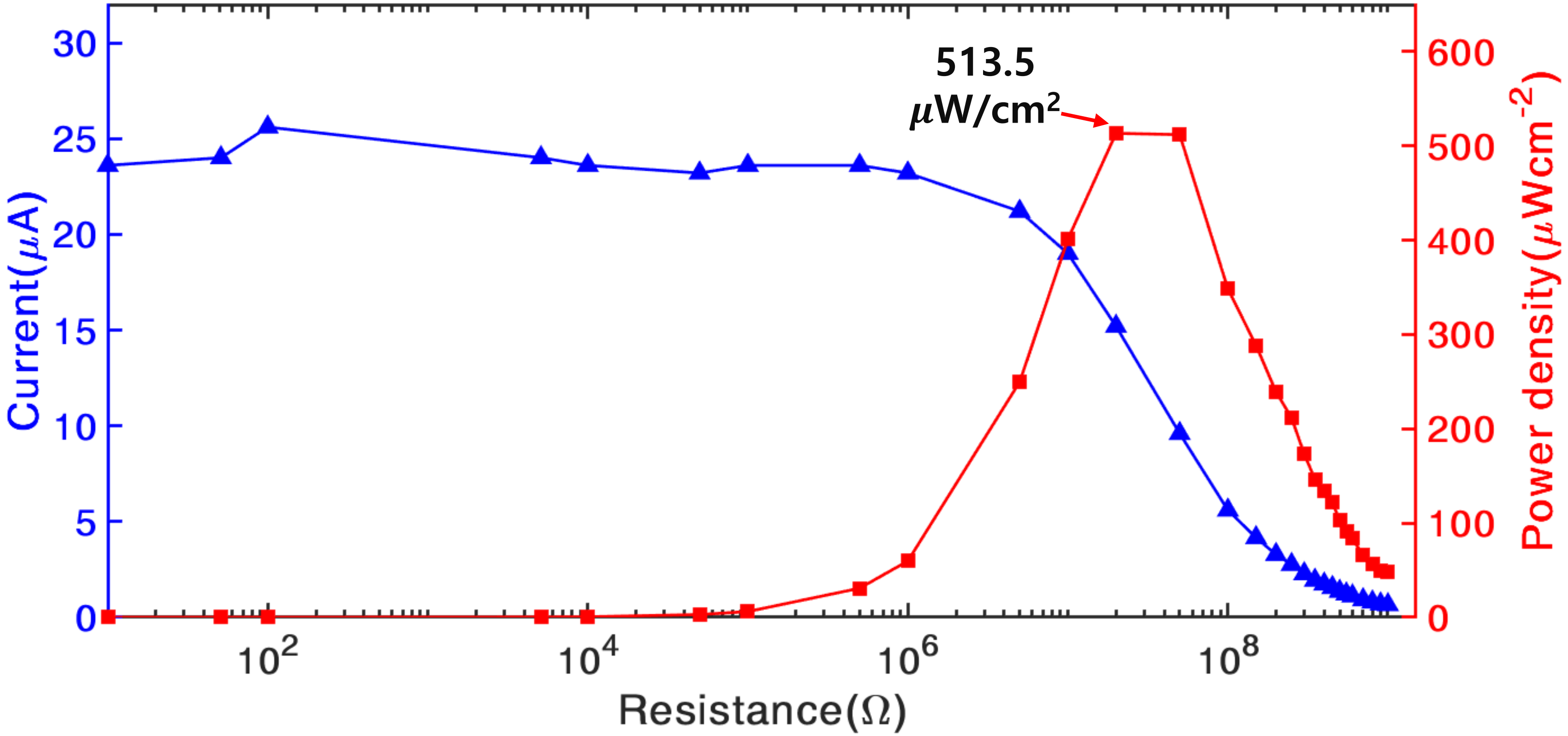
Result

- Current and power density depending on resistance

Tapping distance : 10 mm
Frequency : 5 Hz
Pressing force : 70 N



$$P = IR^2$$

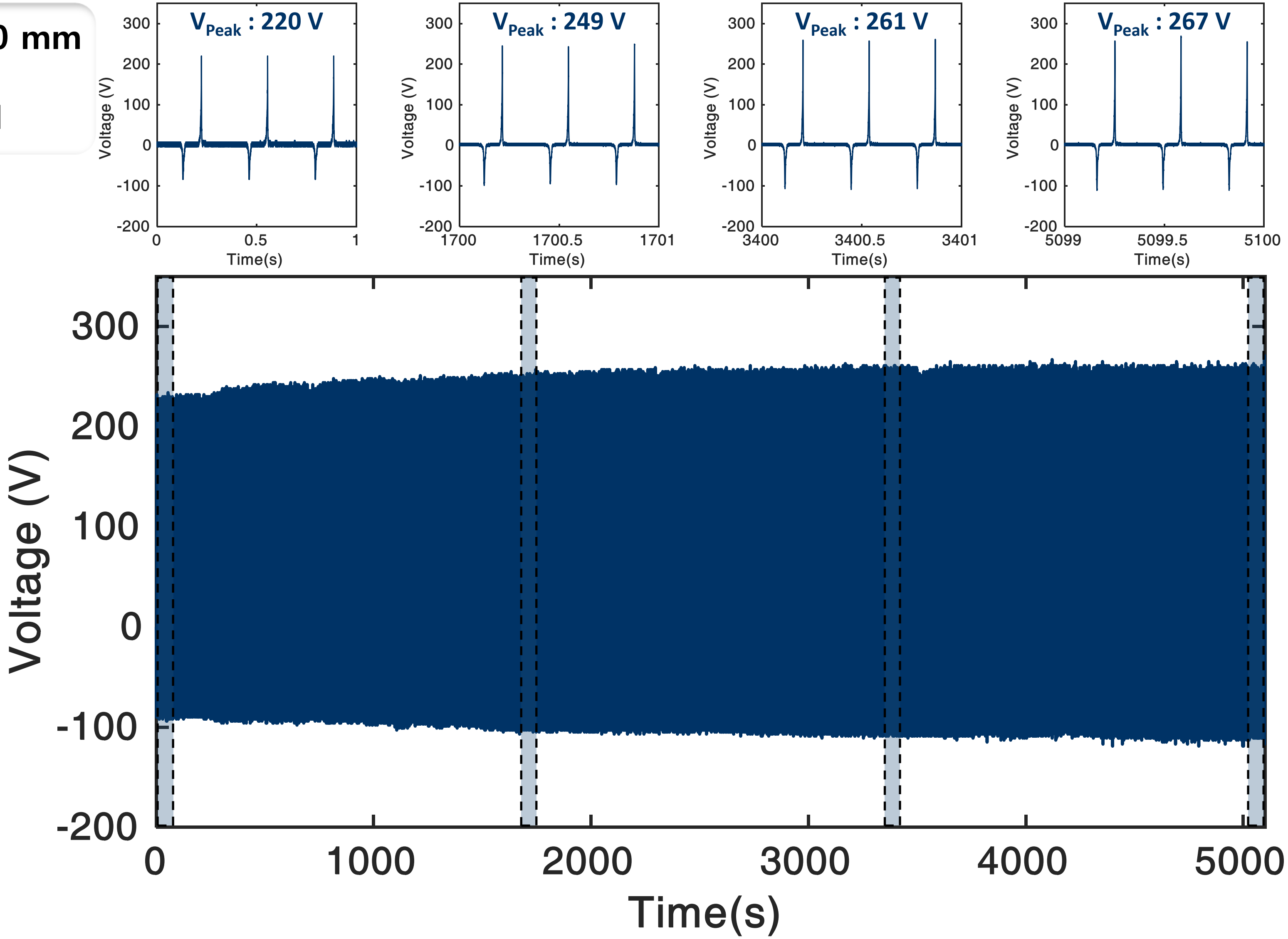


- When a resistance of 20 MΩ was connected, power density of 513.5 μW/cm² was generated.

Result

Voltage variation with prolonged contact-separation

Tapping distance : 10 mm
Frequency : 3 Hz
Pressing force : 70 N

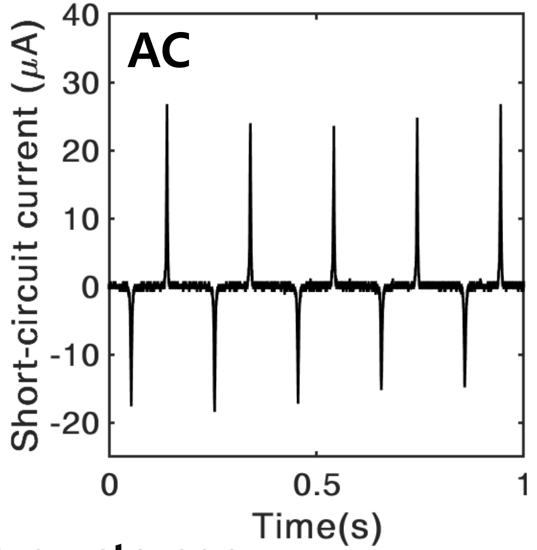


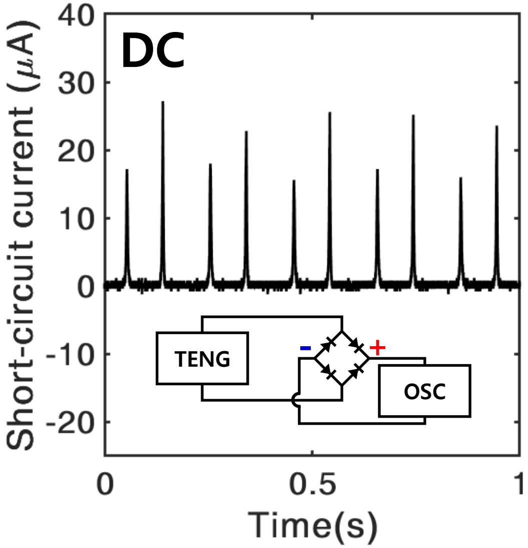
- **Peak output voltage increased gradually from 220 V to 267 V for 5100 sec.**

Result

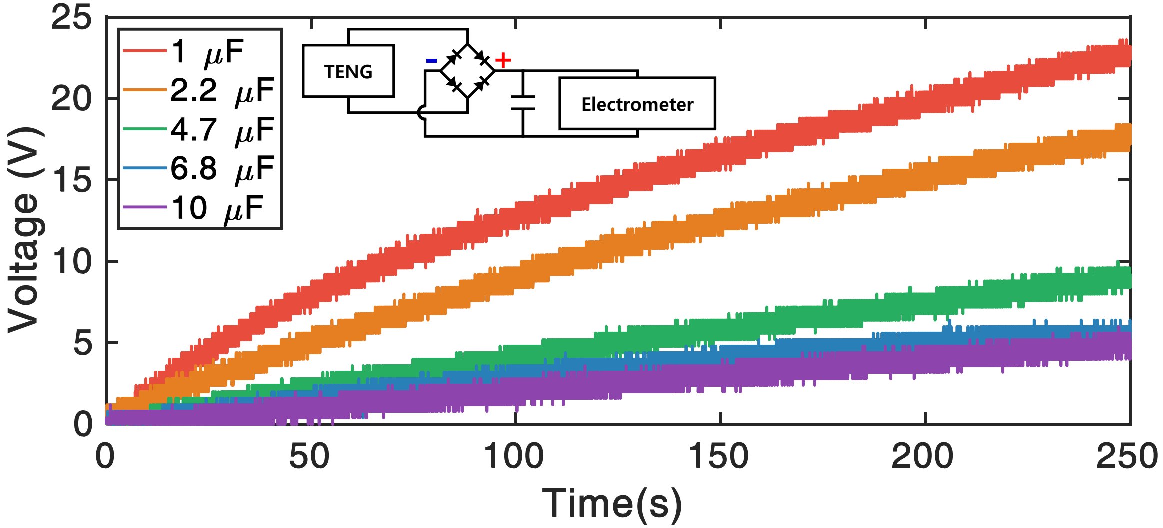
Verification of feasibility of utilizing generated electrical energy

- **Rectification**

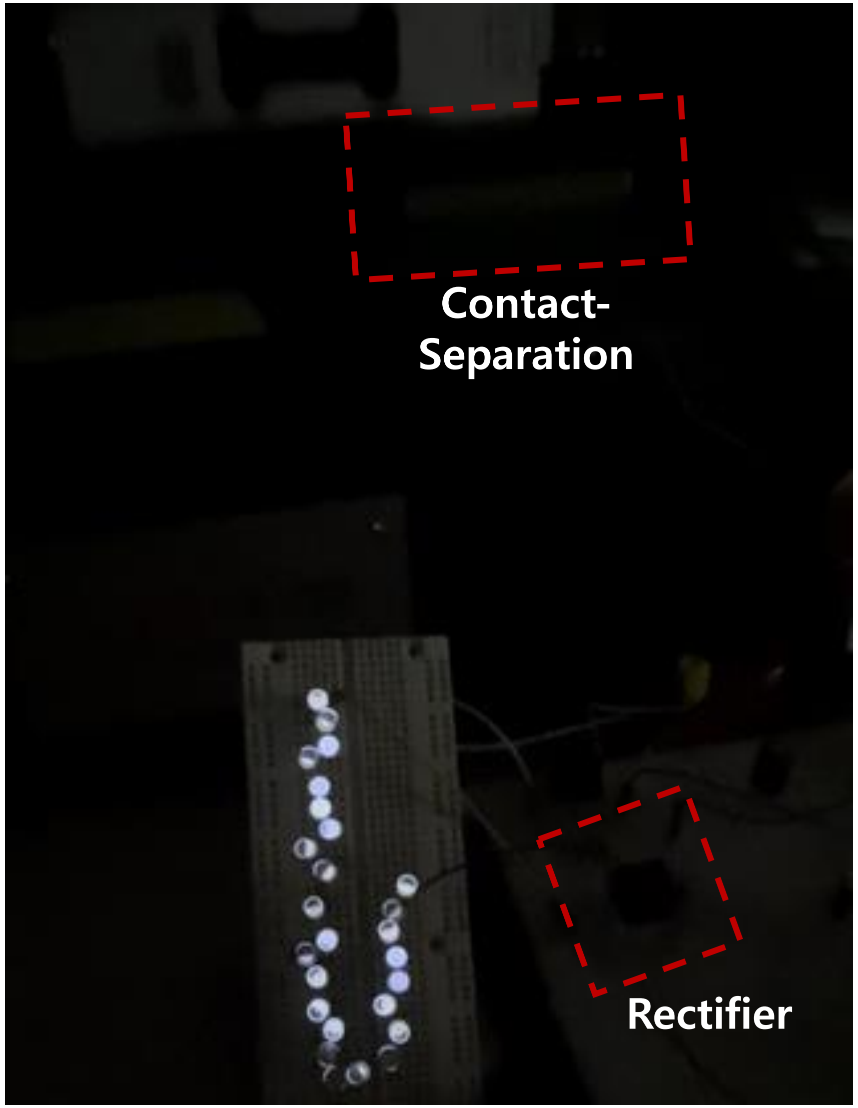




- **Energy storage**



- **Turning on LEDs**



Conclusion

- To capture the mechanical energy generated by the structure, the triboelectrification was applied to the structural material, carbon fiber reinforced plastic.

- Confirmed that changes in voltage, current, and charge occurred in the CFRP and that the amount of electrical energy increased with increasing pressing force and speed.

- A power density of 513.5 $\mu W/cm^2$ was generated when a resistor of 20 MΩ was connected, and it was observed that the generated voltage increased with prolonged contact and separation.

- The electrical energy generated by the composite was rectified and stored, and the LEDs were turned on to verify the energy utilization potential.

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Thank you!

Supporting information

Theoretical basis

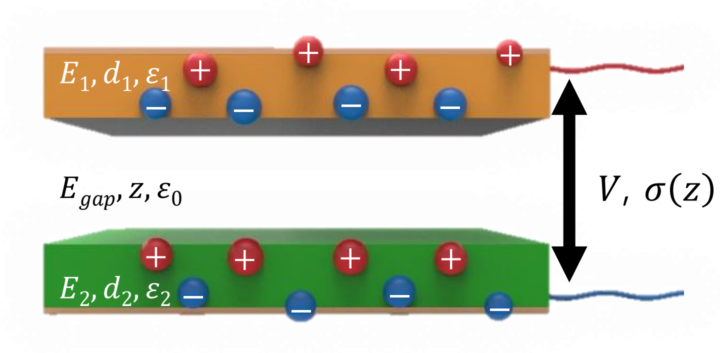
V : Electric potential difference

ε_0 : vacuum permittivity (8.854×10^{-12} F m^{-1})

ε_r : dielectric constant

σ_c : Surface static charge areal density

$\sigma(z)$: Transferred charge density



$$E_1 = \frac{\sigma(z)}{\varepsilon_1}$$

$$E_2 = \frac{\sigma(z)}{\varepsilon_2}$$

$$E_{\text{gap}} = \frac{\sigma(z) - \sigma_c}{\varepsilon_0}$$

$$V = E_1 d_1 + E_2 d_2 + E_{\text{gap}} z$$

$$V = \sigma(z)[\frac{d_1}{\varepsilon_1} + \frac{d_2}{\varepsilon_2}] + \frac{z[\sigma(z) - \sigma_c]}{\varepsilon_0}$$

Under short-circuit condition, $V = 0$

$$\sigma(z) = \frac{z\sigma_c}{\frac{d_1\varepsilon_0}{\varepsilon_1} + \frac{d_2\varepsilon_0}{\varepsilon_2} + \varepsilon_0}$$