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Supplementary Information

A Wearable Thermoelectric Generator Fabricated on a Glass Fabric

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- **TE printing process on the glass fabric (Cross-sectional view)**

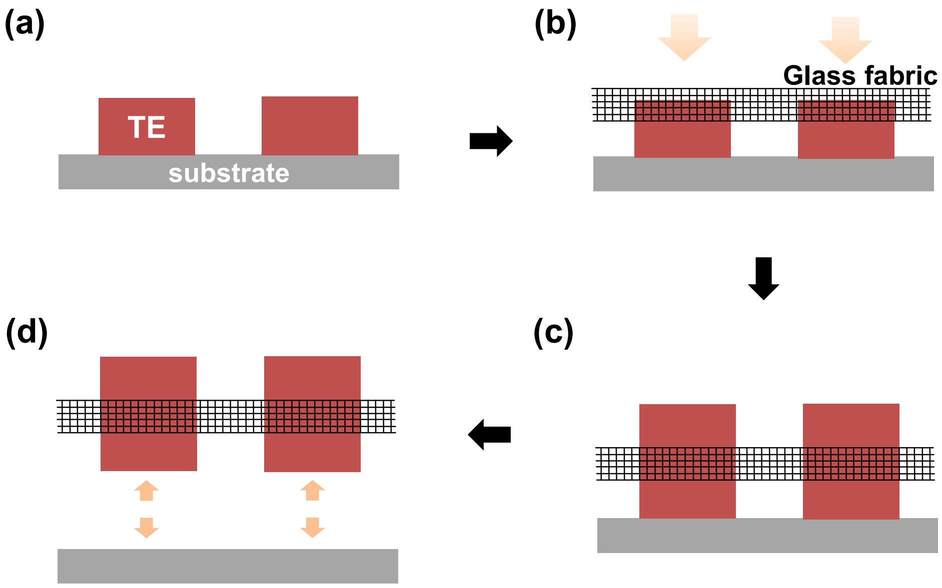

Fig. S1. Schematic illustration of TE printing process on the glass fabric. (a) Printing process of the TE pastes on the Al_2O_3 substrate. (b) Glass fabric on the TE films. (c) Subsequent printing process of the TE pastes on the glass fabric. (d) Removal of the Al_2O_3 substrate after annealing process of the TE films.

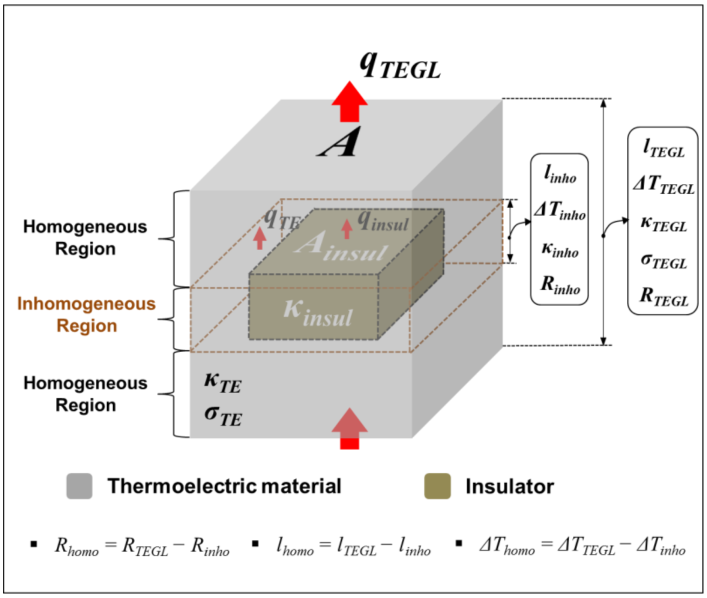

Fig. S2. Schematic illustration and definitions of the terminologies used in the proposed model. This proposed model is used for the calculation of electrical conductivity and thermal conductivity of the suggested structure (hereafter called "TEGL") above, which includes an insulator. The structure is classified into two regions of homogeneous and inhomogeneous parts to simplify the calculation.

Calculation of electrical conductivity

We begin the calculation with the electrical conductivity equation (Eq. (1)) in a steady state, with the definitions shown in Fig. S2.

$$\sigma = \frac{l}{RA} \tag{1}$$

Here, σ is the electrical conductivity, l is the thickness, R is the resistance, and A is the cross-section area. The resistance of the TEGL is the sum of the resistances of the homogeneous and inhomogeneous regions. We thus calculate the resistance of the TEGL (R_{TEGL}) by considering the resistances of the homogeneous (R_{homo}) and inhomogeneous (R_{inho}) regions, as shown in Fig. S2 and Eq. (2).

$$R_{TEGL} = R_{homo} + R_{inho} \tag{2}$$

$$R_{TEGL} = \frac{l_{TEGL}}{\sigma_{TEGL} A} \tag{3}$$

$$R_{homo} = \frac{l_{homo}}{\sigma_{TE} A} = \frac{l_{TEGL} - l_{inho}}{\sigma_{TE} A} \tag{4}$$

$$R_{inho} = \frac{l_{inho}}{\sigma_{TE} \left(A - A_{insul} \right)} \tag{5}$$

where l_{TEGL} is the thickness of the TEGL, l_{homo} is the thickness of the homogeneous region, l_{inho} is the thickness of the inhomogeneous region, σ_{TEGL} is the electrical conductivity of the TEGL, σ_{TE} is the electric conductivity of the TE material, and A_{insul} is the cross-section area of the insulator, as shown in Fig. S2. R_{TEGL}, R_{homo}, and R_{inho} in Eqs. (3), (4), and (5) are plugged into Eq. (2), after which the expression of σ_{TEGL} can be obtained as follows:

$$\sigma_{TEGL} = \left[\frac{1}{\sigma_{TE}} \left\{ \left(1 - \frac{l_{inho}}{l_{TEGL}} \right) + \left(\frac{l_{inho} / l_{TEGL}}{1 - A_{insul} / A} \right) \right\} \right]^{-1} \tag{6}$$

Calculation of thermal conductivity

We begin the calculation of the thermal conductivity of the TEGL with Fourier's law in a steady state (Eq. (7))

$$q = -\kappa A \frac{\Delta T}{l} \tag{7}$$

Here, q is the rate of heat flow, κ is the thermal conductivity, and ΔT is the temperature difference. First, the inhomogeneous region shown in Fig. S2 is considered. The total rate of heat flow across the TEGL, q_{TEGL}, is the sum of the heat flow across the TE material, q_{TE}, and the insulator, q_{insul}, as shown in Eq. (8).

$$q_{TEGL} = q_{TE} + q_{insul} \tag{8}$$

$$q_{TEGL} = -\kappa_{inho} A \frac{\Delta T_{inho}}{l_{inho}} \tag{9}$$

$$q_{TE} = -\kappa_{TE} \left(A - A_{insul}\right) \frac{\Delta T_{inho}}{l_{inho}} \tag{10}$$

$$q_{insul} = -\kappa_{insul} A_{insul} \frac{\Delta T_{inho}}{l_{inho}} \tag{11}$$

where κ_{inho} is the thermal conductivity of the inhomogeneous region, κ_{TE} is the thermal conductivity of the TE material, κ_{insul} is the thermal conductivity of the insulator, and ΔT_{inho} is the temperature difference across the inhomogeneous region. q_{TEGL}, q_{TE}, and q_{insul} in Eqs. (9), (10), and (11) are plugged into Eq. (8), which is expressed as follows:

$$\kappa_{inho} A \frac{\Delta T_{inho}}{l_{inho}} = \kappa_{TE} \left(A - A_{insul}\right) \frac{\Delta T_{inho}}{l_{inho}} + \kappa_{insul} A_{insul} \frac{\Delta T_{inho}}{l_{inho}} \tag{12}$$

Equation (12) can then be summed up as follows:

$$\kappa_{inho} = \kappa_{TE} \left(1 - \frac{A_{insul}}{A}\right) + \kappa_{insul} \frac{A_{insul}}{A} \tag{13}$$

We next calculate the thermal conductivity of the TEGL from the interrelation of the temperature distribution across the TEGL, as follows :

$$\Delta T_{TEGL} = \Delta T_{homo} + \Delta T_{inho} \tag{14}$$

$$\Delta T_{TEGL} = -q_{TEGL} \frac{l_{TEGL}}{\kappa_{TEGL} A} \tag{15}$$

$$\Delta T_{homo} = -q_{TEGL} \frac{l_{homo}}{\kappa_{TE} A} = -q_{TEGL} \frac{l_{TEGL} - l_{inho}}{\kappa_{TE} A} \tag{16}$$

$$\Delta T_{inho} = -q_{TEGL} \frac{l_{inho}}{\kappa_{inho} A} \tag{17}$$

where ΔT_{TEGL} is the temperature difference across the TEGL, ΔT_{homo} is the temperature difference across the homogeneous region, and κ_{TEGL} is the thermal conductivity of the TEGL. ΔT_{TEGL}, ΔT_{homo}, and ΔT_{inho} in Eqs. (15), (16), and (17) are plugged into Eq. (14), and then Eq. (14) is expressed as shown below and can be further simplified into Eq. (19).

$$q_{TEGL} \frac{l_{TEGL}}{\kappa_{TEGL} A} = q_{TEGL} \frac{l_{TEGL} - l_{inho}}{\kappa_{TE} A} + q_{TEGL} \frac{l_{inho}}{\kappa_{inho} A} \tag{18}$$

$$\kappa_{TEGL} = \frac{l_{TEGL}}{\left(l_{TEGL} - l_{inho}\right)/\kappa_{TE} + l_{inho}/\kappa_{inho}} \tag{19}$$

Equation (13) is plugged into Eq. (19), after which the expression of κ_{TEGL} can be obtained as follows :

$$\kappa_{TEGL} = \frac{\kappa_{TE}\left\{\left(\kappa_{insul}/\kappa_{TE} - 1\right)A_{insul}/A + 1\right\}}{\left(1 - l_{inho}/l_{TEGL}\right)\left\{\left(\kappa_{insul}/\kappa_{TE} - 1\right)A_{insul}/A + 1\right\} + l_{inho}/l_{TEGL}} \tag{20}$$

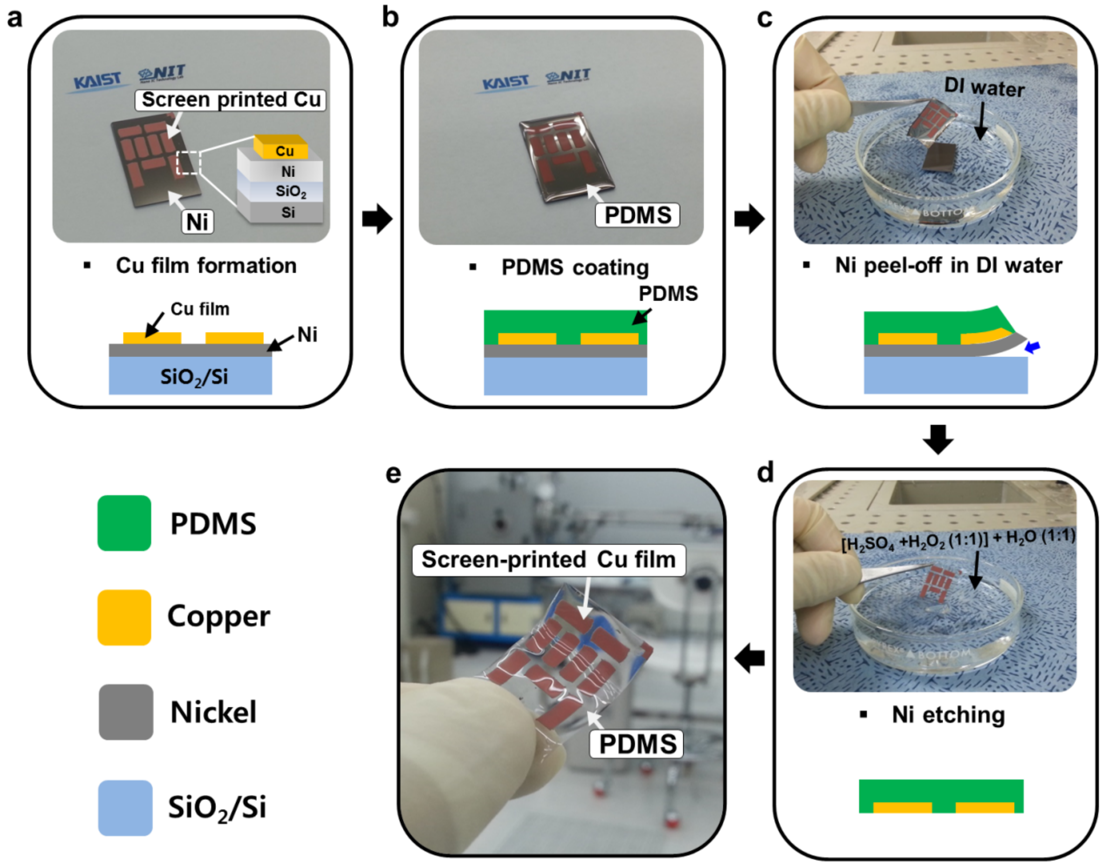

Fig. S3. Process flow of Ni peel-off method. (a) Cu film printing on a Ni/SiO_2/Si wafer. (b) PDMS spin coating at 500 rpm for 30 seconds. (c) Ni peel-off in DI water. Because of the poor adhesion between Ni and the SiO_2 surface, the Ni layer is easily separated from the SiO_2 in water. (d) Removing the remaining Ni layer by etching in a diluted mixture of sulfuric acid and hydrogen peroxide. (e) Finally, the embedded Cu film in PDMS is achieved.

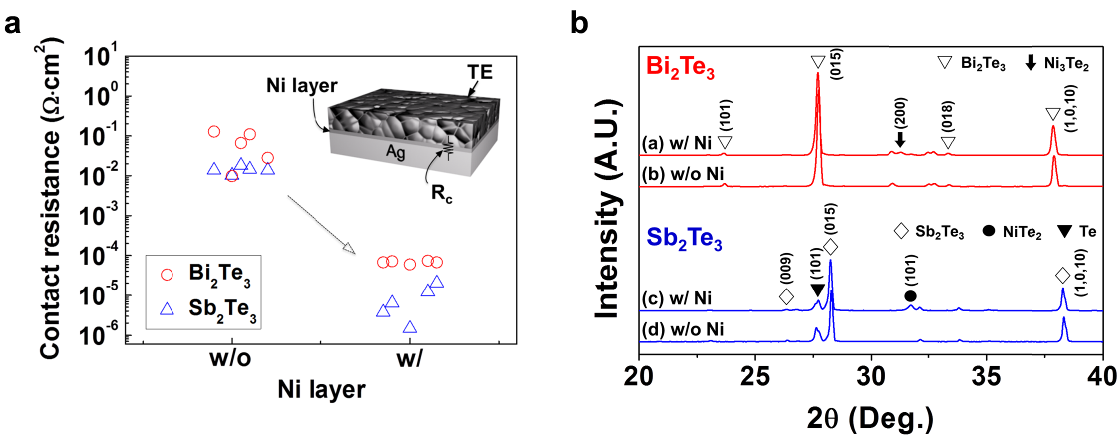

Fig. S4. Analysis of contact resistivity according to incorporation of a Ni layer (a) Specific contact resistivity with and without the Ni layer. The inset shows a schematic illustration. (b) X-ray diffraction patterns of Bi_2Te_3 and Sb_2Te_3 thick films with and without the Ni layer.

Enhancement of contact resistance. In the fabrication process of a flexible TEG, reducing the contact resistance between the TE material and a metal electrode is critical for high output power density. Here, a Ni layer (200 nm) deposited by thermal evaporation is inserted to achieve low contact resistance (inset of Fig. S4a). A cross-bridge Kelvin resistance (CBKR) structure is utilized to extract the interfacial specific contact resistivity using a semiconductor parameter analyzer (Agilent 4156C). Figure S4a shows the change of the specific contact resistivity by inserting a Ni layer. It is worth noting that the contact resistances of Bi_2Te_3 and Sb_2Te_3 with a Ni layer reach 6×10^{-5} $\Omega\cdot cm^2$ and 9×10^{-6} $\Omega\cdot cm^2$, respectively, which are more than 3 orders of magnitude lower than those of the films without the Ni layer. XRD analysis results in Fig. S4b suggest that the contact resistance reduction might be due to the formation of Ni-Te alloys at the interface[42,43].

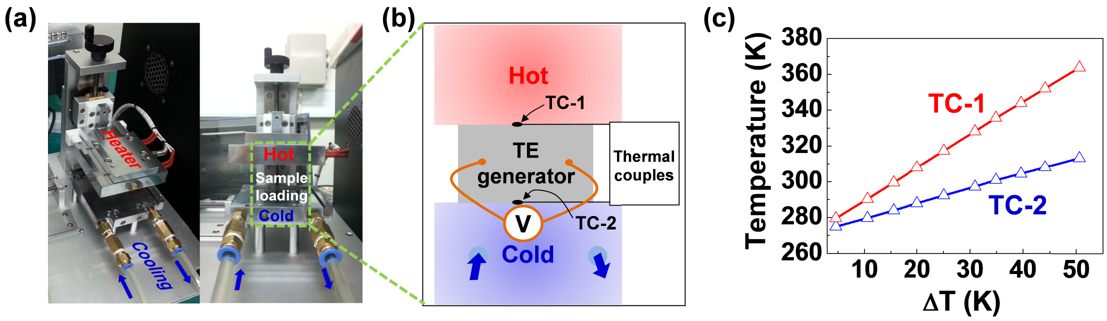

Fig. S5. (a) Photograph of the system used in the measurement of the device performance. (b) Schematic illustration of the measurement system. (c) The temperatures measured by TC-1 and TC-2 at both sides of the glass fabric-based TE generator.

Supplementary references

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