Supporting Information

Vertically and horizontally drawing formation of Graphite Pencil Electrodes on Paper using Frictional Sliding for Disposable and Foldable Electronic Device

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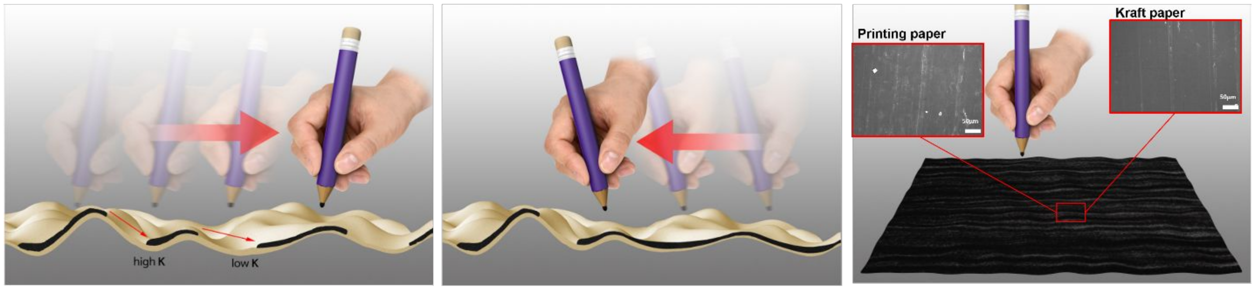

Figure S1. Schematic image of the fabrication of electrode. The surface roughness values of paper were measured by SEM image (Insert), 50 times drawing of graphite pencil (6B) in printer paper and kraft paper.

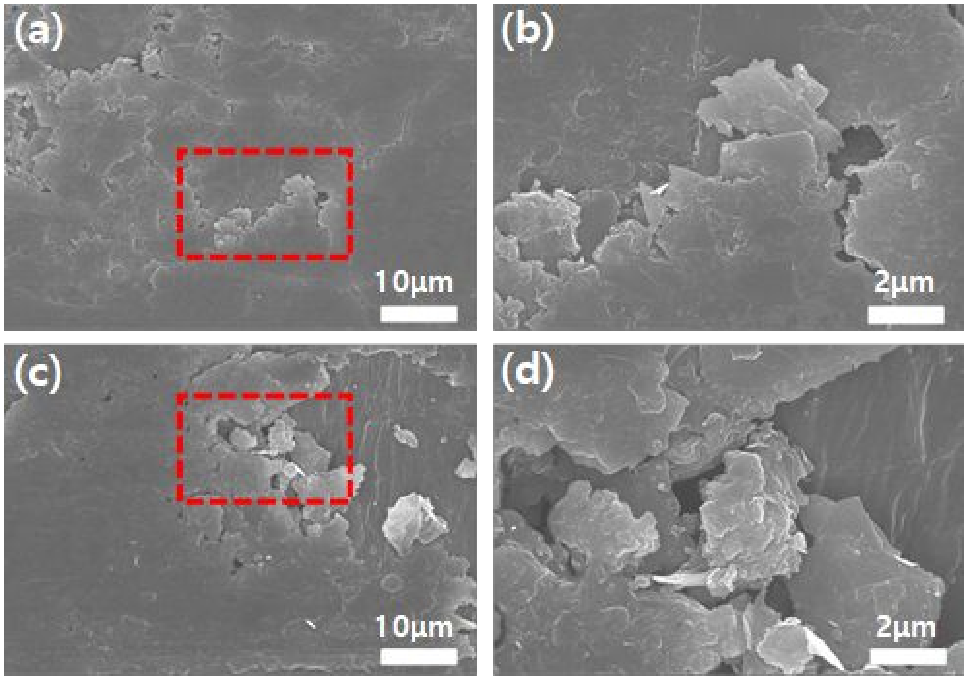

Figure S2. SEM image of graphite particle when drawing on the paper. a) SEM image of graphite electrode when drawing 20 times on the printing paper, b) SEM image of magnified red box on an electrode made of printing paper, c) SEM image of graphite electrode when drawing 20 times on the kraft paper, d) SEM image of magnified red box on an electrode made of kraft paper.

Stick-slip equation

The net force F generated when a slider, which is a substance sliding by an external force (T) on a substrate, generated frictional force by the roughness of the surface of the substrate, is as follows: [1,2]

$$F = T - \mathcal{F}_k \qquad \text{(S1)}$$

where F is the net force, T is the external force, and $\mathcal{F}_k$ is the kinetic frictional force. Also, the external force (T) at some point after the motion starts is as follows: [1,2]

$$T = K(vt - x) + \mathcal{F}_s \qquad \text{(S2)}$$

where K is a constant in the frictional sliding phenomenon, v is the drive velocity at the time of movement, t is the time, x is the displacement, and $\mathcal{F}_s$ is the static frictional force. When the slider is moved by an externally applied force (T), the time must be calculated from the moment the slider begins to move. After the time t second the slider has moved, there is a distance the slider has traveled, which can be denoted by vt. Also, when t = 0, which is the initial condition, x = 0 and dx / dt = 0. (S3)

Substituting Eq, (S1) into Eq. (S2), and changing it is as follows:

$$\mathrm{F} + \mathcal{F}_k = K(vt - x) + \mathcal{F}_s \quad \text{(S4)}$$

Here, the force F and the acceleration a can be expressed as follows:

$$\mathrm{F} = \mathrm{ma}, \ \mathrm{a} = \frac{d^2x}{dt^2} \quad \text{(S5)}$$

Therefore, the force F generated when frictional sliding occurs due to paper surface roughness can be expressed as follows:

$$\mathrm{m}\frac{d^2x}{dt^2} = \mathrm{K(vt - x)} + (\mathcal{F}_s - \mathcal{F}_k) \quad \text{(S6)}$$

When the roughness increases, the friction force increases, and at the same time, the friction force F received by the object must be increased. As 'F' increases, more force is applied to the graphite pencil, so graphite is more absorbed to the surface of the paper substrate at stick-slip motion. Therefore, using the above equation, it can be seen that the Kraft paper having relatively larger surface roughness has lower resistance than the printing paper.

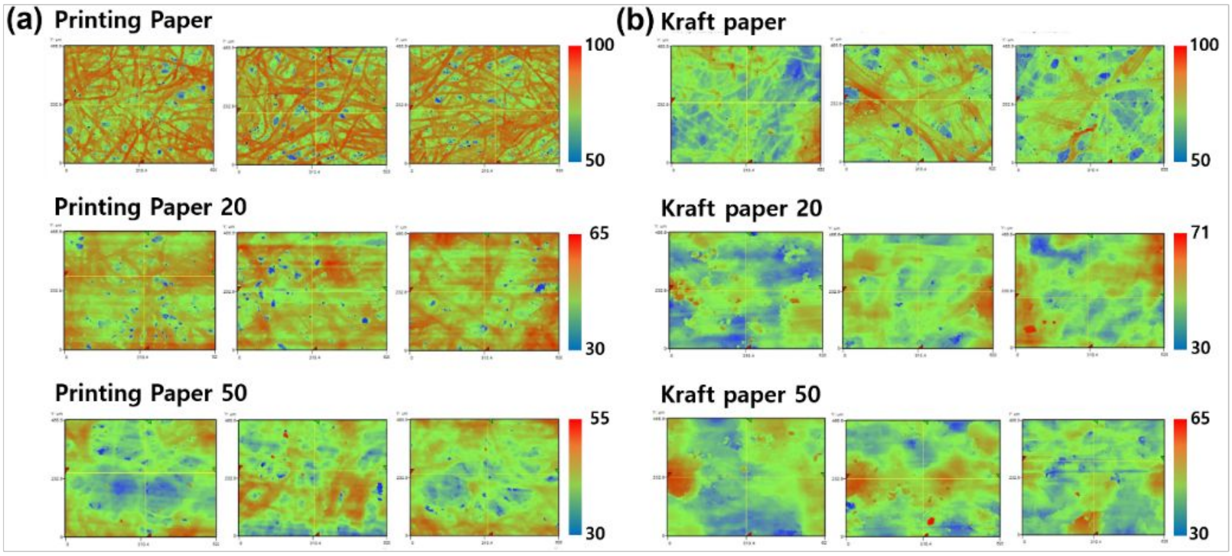

Figure S3. The surface roughness of a paper substrate measured by a 3D optical profile. (a), (b) Printing paper and Kraft paper shows 8B graphite pencil at 0, 20 and 50 times, respectively.

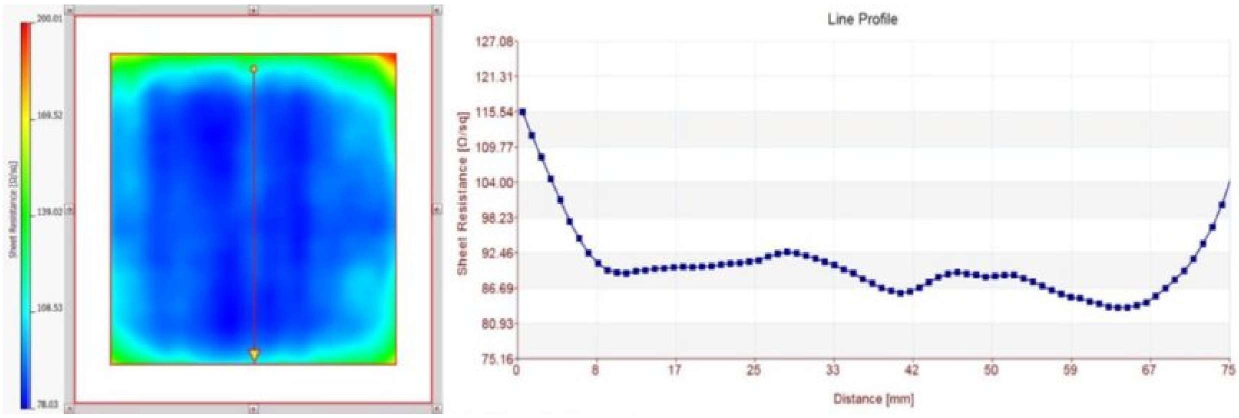

Figure S4. Non-contact sheet resistance mapping results measured by 'TF map 2525SR' in SURAGUS, Germany; (scanning area = (100 mm × 100 mm), scanning pitch = 1 mm in the x and y direction). An electrode formed by drawing 6B graphite pencil 50 times on Kraft paper.

Pressure equation

When drawing by hand 50 times, the same resistance as the pencil hardness tester was obtained, so the pressures applied at the drawing 50 times were compared in order to check the error in the pressure generated at drawing by hand.

For the pencil hardness tester, when drawing one time, the electrode having 10cm x 1cm was drawn with speed of 10mm/s for 10 seconds with the pressures of 3.8kPa(50g of weight), 7.8kPa(100g of weight), 11.8kPa(150g of weight), 15.8kPa(200g of weight), 19.8kPa(250g of weight), 23.8kPa(300g of weight), and 27.8kPa(350g of weight), respectively. At this time, the pressure P applied to the pencil hardness tester can be obtained using the following equation.

$$\mathrm{P} = \frac{\mathrm{F}}{\mathrm{A}} = \frac{ma}{A} \qquad \text{(S7)}$$

Here, 'P' refers to the pressure, 'F' refers to the force, 'A' refers to the area of the electrode drawn, 'm' refers to the mass of weight, and 'a' refers to the acceleration.

When a 0.35kg weight is used, the applied pressure can be obtained as follows.

Acceleration, a = $10\mathrm{mm/s} \div 10s = 1\mathrm{mm}/s^2$

Area of pencil lead, A = $1.26\mathrm{cm}^2 = 1.26*10^{-5}\ \mathrm{m}^2$

Pressure, P = $\frac{0.35kg \times 1mm/s^2}{1.26 * 10^{-5}\ m^2}$ = 27.8 kPa

From the above calculation, it is confirmed that when the heaviest weight of 35g was used in this experiment, a pressure of 27.8kPa was applied.

Weight(g)	50	100	150	200	250	300	350
Pressure(kPa)	3.8	7.8	11.8	15.8	19.8	23.8	27.8

Joule's equation

P, Power can be expressed as the following equation.

$$P = \frac{W}{\Delta t} = \frac{\Delta U}{\Delta t} \tag{S8}$$

The internal energy U is follows;

$$\Delta U = V\Delta Q \tag{S9}$$

therefore

$$P = \frac{V\Delta Q}{\Delta t} = IV = I^2 R \tag{S10}$$

Here, for the heat value H

$$H = Pt = I^2 Rt = \frac{V^2}{R} t \tag{S11}$$

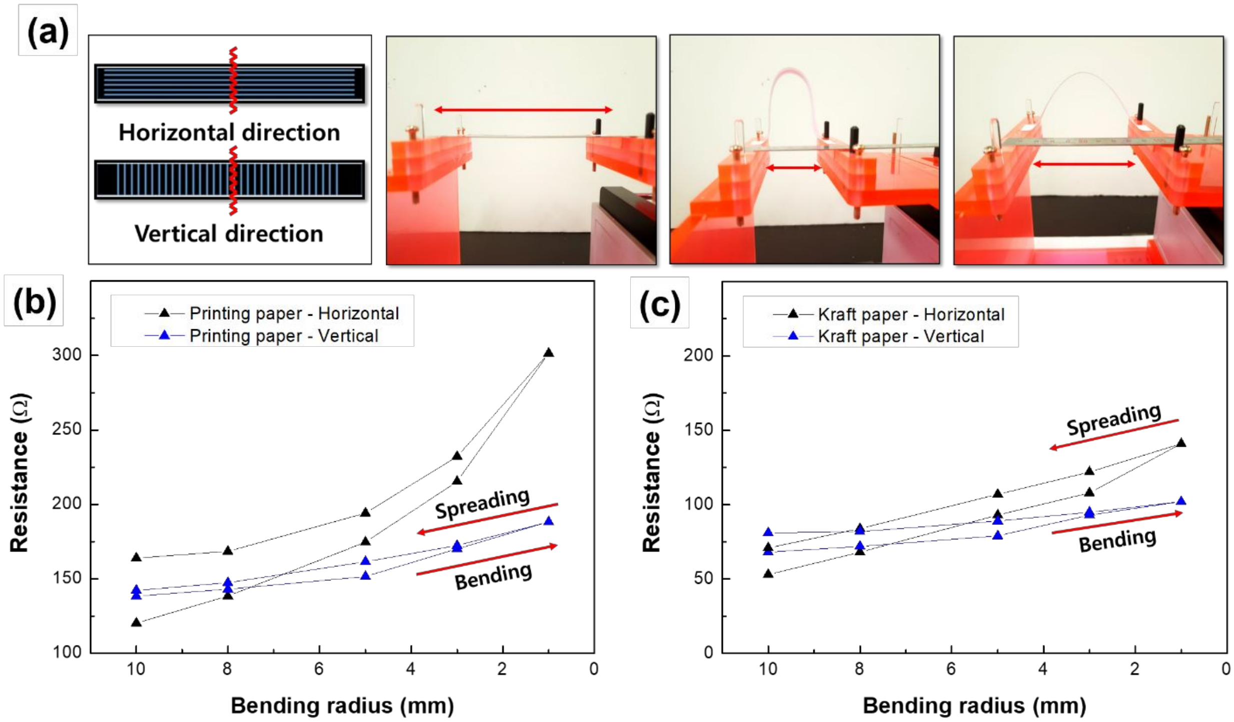

Figure S5. Resistance change according to bending radius and bending cycle of electrode formed on paper. (a) A simple conceptual diagram of the electrode (left), and a bent shape (right). (b) and (c) Resistance change when the electrode is bent and spread again; (b) printing paper, (c) kraft paper.

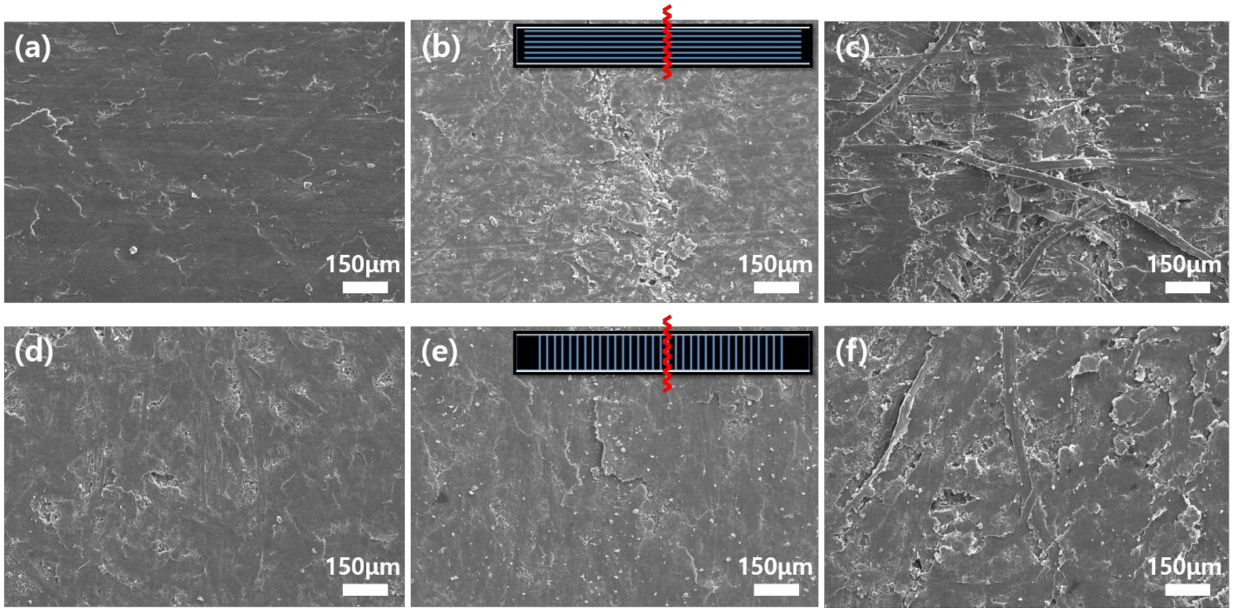

Figure S6. A SEM image obtained by measuring cracks occurred in the bending test to the electrodes in the horizontal and vertical drawing directions. The images show the cracks occurred; a) at horizontal direction pristine electrode, b) and c) at bending the horizontal direction electrode, d) at vertical direction pristine electrode, and e) and f) at bending the horizontal direction electrode.

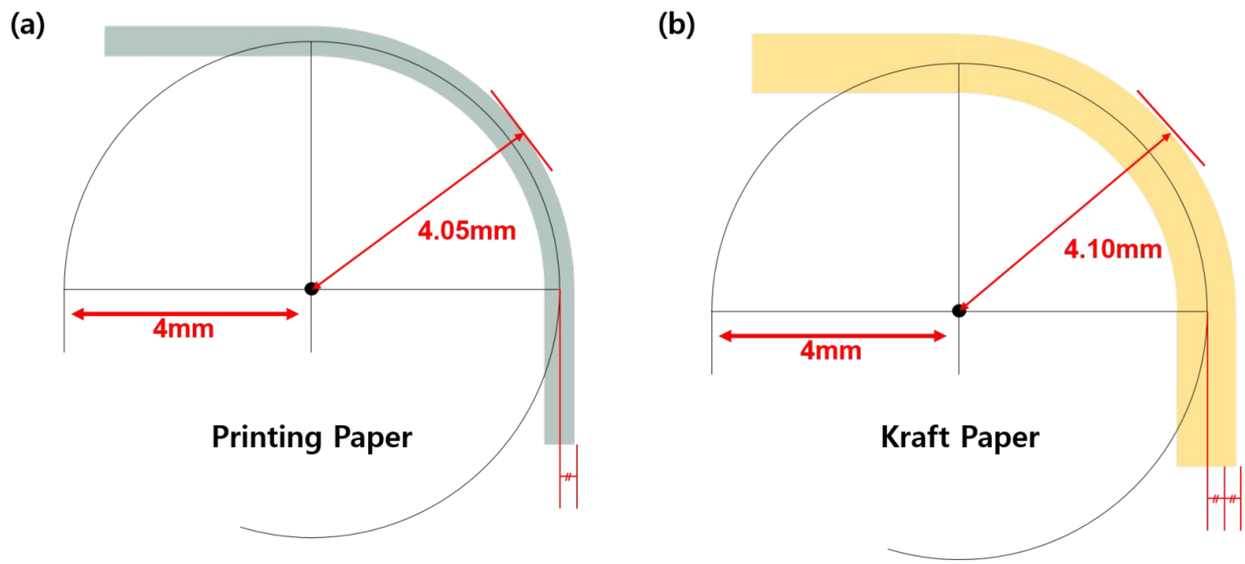

Figure S7. A simple schematic to show the amount of change in length of the outer surface with respect to the thickness of the object when the object is bent. a) in case of the printing paper, b) in case of the kraft paper

	Printing paper R_q (μm)			Average R_q (μm)
Pristine	5.45	5.36	4.77	5.19
20 times drawing	1.48	1.26	1.50	1.41
50 times drawing	1.29	1.23	1.35	1.29
Pencil hardness tester 50 time drawing	1.14	1.16	1.12	1.14
	Kraft paper R_q (μm)			Average R_q (μm)
Pristine	6.15	6.11	5.70	5.99
20 times	2.23	2.20	2.23	2.22
50 times	1.65	1.83	2.02	1.83
Pencil hardness tester	1.65	1.89	1.84	1.79

50 time drawing				

Table S1. The surface roughness values of paper measured by 3D optical profile with (0, 20, 50) times drawing of graphite pencil (6B) in printing paper and kraft paper, and when Super P solution was coated. (R_q = Root mean square of roughness).

	Printing paper R_q			Average R_q
Pristine	5.04	5.85	4.73	5.21
20	2.02	1.56	1.99	1.86

Table S2. The surface roughness values of paper measured by 3D optical profile with (0, 20, 50) times drawing of graphite pencil (8B) in printing paper and kraft paper.

50	1.96	1.93	1.53	1.81
	Kraft paper R_q			Average R_q
Pristine	5.94	5.76	5.81	5.84
20	2.23	2.57	2.34	2.53
50	2.43	2.11	2.14	2.23

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1. Berman, A.D.; Ducker W.A.; Israelachvili J.N.; Origin and Characterization of Different Stick-Slip Friction Mechanisms. *Langmuir,* **1996**, *12*, 4559-4563.

2. Setiyana, B.; Ismail, R.; Jamari, J.; Schipper, D. J. Stick-Slip Behaviour of a Viscoelastic Flat Sliding along a Rigid Indenter. *Tribology Online* **2016**, *11*, 512-518.