Supporting Information for

Flexible and Robust Hybrid Paper with Large Piezoelectric Coefficient

*Suresha K. Mahadeva*, Konrad Walus, and Boris Stoeber

1Department of Electrical and Computer Engineering, The University of British Columbia

2332 Main Mall, Vancouver, BC V6T 1Z4, Canada

2Department of Mechanical Engineering, The University of British Columbia

2054-6250 Applied Science Lane, Vancouver, BC V6T 1Z4, Canada

*Email: sure1977@mail.ubc.ca, suresha_km@hotmail.com*
Figure S1. Current-Voltage (I-V) sweep curve of the piezoelectric paper, the voltage $V$ was scanned between -0.5 V and +0.5 V and the resulting dc current $I$ was measured using a source meter (Keithley 2635A). The electrical conductivity

$$\sigma_s = \frac{\Delta I}{\Delta V} \frac{L}{A},$$

was then calculated using the slope of the current versus voltage curve $\Delta I/\Delta V$, the thickness $L = 0.011$ cm, and the area $A = 1$ cm$^2$ of the sample, to yield $\sigma_s = 9.19 \times 10^{-7}$ S/cm.
(1) Scissor cut Piezoelectric Paper (2.5 cm x 2.5 cm)

(2) Scissor cut Laminating Pouches (4 cm x 4 cm)

(3) Deposit Silver Electrode on Laminating Pouches Using Conductive Ink Dispenser (2 cm x 2 cm)

(4) Sandwiching Piezoelectric Paper between Electroded Laminating Pouches

(5) Hot Lamination Using Office Laminator and wiring

Figure S2. Step-by-step process showing a novel process for fabricating paper based accelerometer.
Figure S3: Compared TEM images of BaTiO$_3$ functionalized wood fiber before (a) and after (b) activating in CMC suspension, wood fibers appears larger than that of their counterparts due to coverage of CMC.

Figure S4. Stress-strain curves of hybrid paper as a function of CMC concentration.
Figure S5. Piezoelectric response of hybrid paper aged for 14 months.

Figure S6. Force-displacement curve of paper laminate subjected to compression load using Bose Electro force.
Figure S7. Compared output signal measured from commercial reference accelerometer; ADXL203 EB by Analog Devices (left), and paper accelerometer (right) at 30 Hz and 0.18 g acceleration amplitude. Note that output signal recorded from the paper accelerometer is similar and matches with a reference accelerometer.
Estimated Cost for Preparing φ11 cm Hybrid Piezoelectric Paper

**Material Cost**

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity Required</th>
<th>Rate</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp</td>
<td>2 g</td>
<td>$1/kg</td>
<td>$0.002</td>
</tr>
<tr>
<td>NaCl</td>
<td>9 g</td>
<td>$10.5/kg</td>
<td>$0.095</td>
</tr>
<tr>
<td>PSS</td>
<td>1 g</td>
<td>$51.4/100g</td>
<td>$0.51</td>
</tr>
<tr>
<td>PDDA</td>
<td>2 g</td>
<td>$41.7/kg</td>
<td>$0.08</td>
</tr>
<tr>
<td>BaTiO₃ NPs</td>
<td>2.52 g</td>
<td>$263/kg</td>
<td>$0.66</td>
</tr>
<tr>
<td>NaCMC</td>
<td>0.5 g</td>
<td>$111/kg</td>
<td>$0.056</td>
</tr>
</tbody>
</table>

Total Material Cost: $1.4

Electric Charges for Poling

Electric energy required for Poling

\[
\text{Electric energy} = \text{Oven} + \text{Voltage source} = 9.6 \text{ kWh} + 0.12 \text{ kWh} = 9.72 \text{ kWh}
\]

Electric tariff = $0.59/h

Electric Charges for Poling = 9.72 × $0.59 = $5.74

Cost for Preparing φ11 cm Hybrid Piezoelectric Paper = $1.4 + $5.74 = $7.14

NaCl- sodium chloride, PSS- poly(sodium 4-styrenesulfonate), PDDA- poly(diallyldimethylammonium chloride), NaCMC- sodium carboxymethylcellulose, BaTiO₃ NPs- barium titanate nanoparticles
Paper Accelerometer Model

Paper accelerometer configuration

Free-body diagram of seismic mass

$$a = \ddot{Z} = -\omega Z$$

$$F_k = m\ddot{Z}_m$$

$$F_k = k(Z - Z_m)$$

harmonics:

$$Z_m = Z_m\omega_s\omega_t$$

$$Z_m = -\omega^2 Z_m \cos \omega t = -\omega^2 Z_m$$

$$F_m = m\ddot{Z}_m = -m\omega^2 Z_m = k(Z - Z_m)$$

$$Z_m = \frac{k}{k - m\omega^2} Z = \frac{Z}{1 - (\omega/\omega_0)^2} \quad \text{with} \quad \omega_0 = \sqrt{k/m}$$

$$Q = D_3 A_3 = d_{33}^A \omega = d_{33}^m (-\omega^2) Z_m$$

$$Q = \frac{d_{33} m}{1 - \left(\frac{\omega}{\omega_0}\right)^2}(-\omega^2)Z = \frac{d_{33} m}{1 - \left(\frac{\omega}{\omega_0}\right)^2}a$$

$$Q = \frac{d_{33} m}{1 - \left(\frac{\omega}{\omega_0}\right)^2}$$

$$f_0 = \frac{1}{2\pi} \sqrt{k/m}$$