Ultra-thin and conductive nanomembrane arrays for nanomechanical transducers**

By Tae June Kang, Misun Cha, Eui Yun Jang, Jaeha Shin, Hyeong Uk Im, Yunho Kim, Junghoon Lee, and Yong Hyup Kim*

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Supporting Information

Stacking strategy for nanomembranes

Figure S1 shows a schematic flow of stacking strategy for SWNT embedded nanomembrane based on ESA method. Positively charged PAH monolayer is formed by using a spin-coating of PAH solution in conjunction with the washing-out process of excessive PAH (Fig. S1-(1)). And then, in the same manner, negatively charged PSS monolayer can be formed on PAH (Fig. S1-(2)). The procedure is repeated until the desired number of polymer bilayers is accumulated based on ESA. The top-surface of the polymer bilayers should be terminated with PAH layer to electrostatically conjugate the SWNT interlayers (Fig. S1-(3)). Purified and chemically functionalized SWNTs with hydroxyl and carboxyl chemical groups are spin-coated on the PAH layer (Fig. S1-(4)), and electrostatic interactions are generated between the PAH and SWNTs. PAH layer is coated on the SWNT layers once more, and then, polymer bilayers are formed (Fig. S1-(5)). This deposition strategy prevents phase segregation of the polymer/SWNT binary system, which is a typical failure-mechanism of hybrid materials primarily attributed to poor matrix-SWNT interfacial strength.
Mechanical properties from the measured capacitance changes

In the present study, the change of capacitance between nanomembrane and a metal electrode was converted to a deflection of the nanomembrane subjected to the hydraulic pressure controlled by a water volume, and then, the residual stress and elastic modulus of nanomembranes were evaluated. A scheme of the set-up, measurement of capacitance changes with the different density of SWNT interlayers are presented in Fig. S2.
Figure S2. Capacitive-type bulging test for the measurement of mechanical properties of nanomembranes. (a) Schematic diagram of the bulge setup with a metal electrode held from the nanomembrane by an insulating spacer, and nanomembranes are bulged with hydraulic pressure. (b) In-situ measurement of changes in capacitance between the bulged nanomembranes. (c) Capacitance changes of nanomembranes with the different density of SWNT interlayers with respect to the applied pressure.

Deflection of square membrane under the uniform pressure loading can be calculated as following:

$$ p = 3.393 \frac{\sigma_0 t \times w_{\text{max}}}{(l/2)^2} + (1.996 - 0.613 \nu) \frac{Et}{(1-\nu)} \frac{w_{\text{max}}^3}{(l/2)^3} $$

Where $p$ and $w_{\text{max}}$ represent the applied uniform pressure and the central deflection of membrane, respectively, and unknown value of $\sigma_0$ and $E$ denotes the residual stress and the elastic modulus of membrane, respectively. $t$ (thickness) and $l$ (lateral dimension of square membrane) represent the geometry of membrane, and Poisson ratio of $\nu$ is assumed as to be 0.3.

The applied pressure can be determined by the geometry of well and the controlled water volume as shown in Fig. S3, and the change of capacitance was converted to a deflection of the membrane as following;
\[ w = \varepsilon \cdot A \left( \frac{1}{C_0} - \frac{1}{C_m - C_p} \right), \text{ and } C_0 = \frac{\varepsilon \cdot A}{g_0} \]

Where \( C_0, \ C_m \) and \( C_p \) represent the initial capacitance, measured capacitance and the parasitic capacitance of the system, respectively. \( \varepsilon \) denotes the permittivity, and \( A \) represent the area of membrane.

**Figure S2.** Determination of controlled hydraulic pressure from the geometry of well and the controlled water volume.

Mechanical properties such as the residual stress and elastic modulus of nanomembranes were evaluated from the simultaneous equations with respect to the different applied pressure as following;

\[
\begin{bmatrix}
\sigma_0 \\
\sigma_2
\end{bmatrix} = \begin{bmatrix}
\frac{3.393 t \times w_1}{(l/2)^2} & (1.996 - 0.613 \nu) \frac{t}{(1 - \nu)(l/2)^4} w_1^3 \\
\frac{3.393 t \times w_2}{(l/2)^2} & (1.996 - 0.613 \nu) \frac{t}{(1 - \nu)(l/2)^4} w_2^3
\end{bmatrix}^{-1} \begin{bmatrix}
p_1 \\
p_2
\end{bmatrix}
\]