Supplementary Information for:

Super-stretchable, Transparent Carbon Nanotube-Based Capacitive Strain Sensors for Human Motion Detection

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Supplementary Figures and Texts

1. In situ electrical measurements and morphological observations

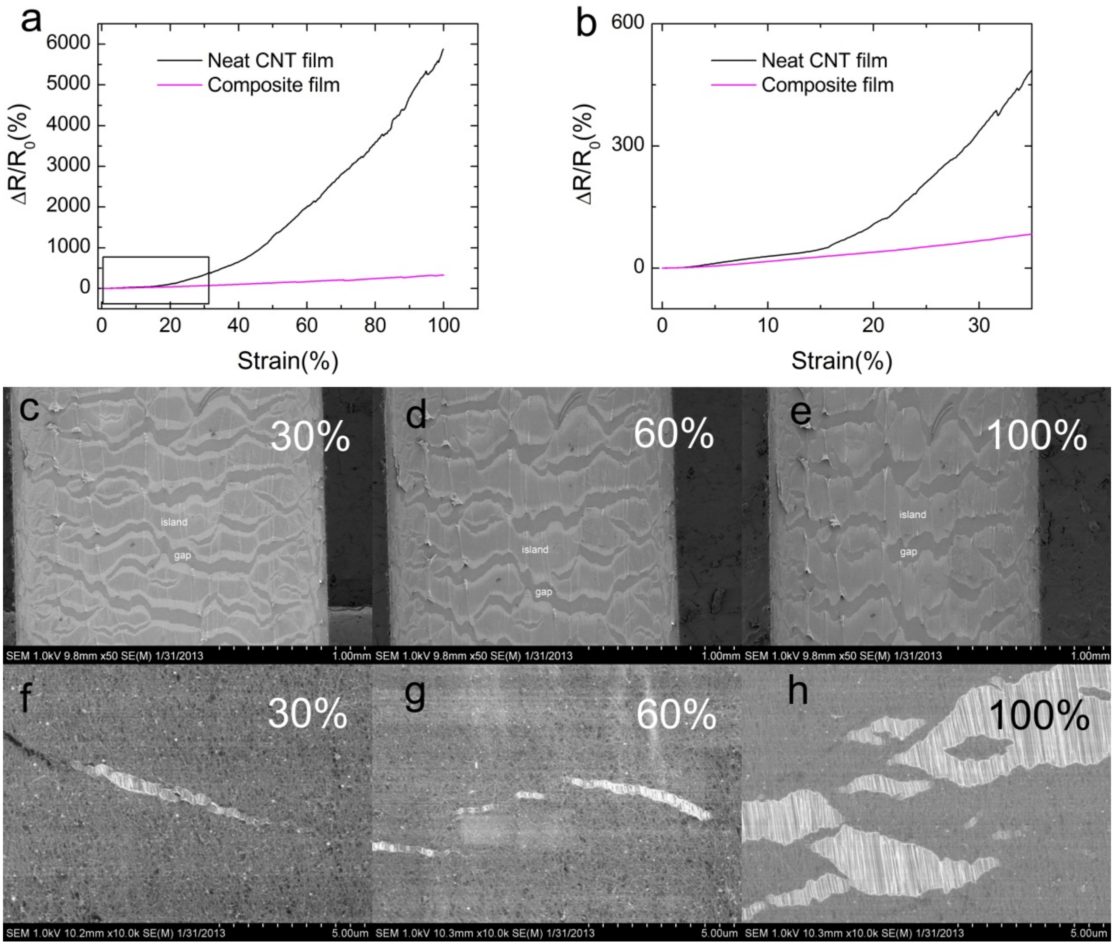

Figure S1. In situ electrical measurements and morphological observations. a, Resistance changes under uniaxial strain up to 100%. **b,** A close look at the part in the rectangular frame in **a**. **c-h,** Morphological changes under different uniaxial strains for neat CNT film and composite film. Note that the scale bars are 1 mm and 5 μm for neat film and composite film, respectively.

To highlight the role of silicone matrix, we conducted in situ SEM characterizations on both neat CNT films and CNT/PDMS composite films (See Supplementary Fig. S1). The resistance of neat films rose steeply when the applied strain exceeded ~15%, as a result of the ubiquitous gaps with sizes up to around 100 μm which were initiated by the stress concentration at weak points in the pristine films. CNT/PDMS composite films, in contrast, showed relatively moderate increase in resistance and only occasional, several-micrometer-sized gaps even under strains as high as 100%. The silicone matrix evidently mitigated the concentration of stress, not only maintaining the structural integrity but also relieving the resistance increase of the composite films, both of which were beneficial for improving the strain gauging performances of the final devices.

2. Capacitive characteristics under 0 and 100% strain

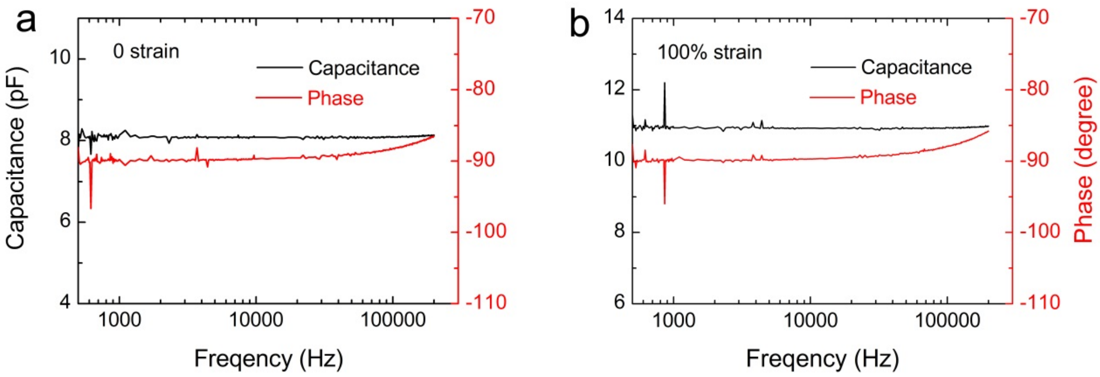

Figure S2. Bode plots of a CNT-based capacitive strain gauge. a, Under 0 strain. **b,** Under 100% strain.

We measured the capacitance value of CNT-based transparent strain gauge in response to frequency sweep in the range of 40-200k Hz. The strain gauge exhibited excellent capacitive characteristics (phase angle ~ -90^{o}C), under both 0 and 100% strains, providing that excitation frequency was below ~ 10 kHz. Higher excitation frequency was beneficial to obtaining a high signal-to-noise ratio, so we chose an excitation frequency of 5 kHz in the tensile stretching tests.

3. Treatments of the raw data

The experimental data deviated from the linear predictions when the applied strains exceeded 50% (shown in Fig. S3 a), which was attributed to the effects of the clamps. In order to obtain the intrinsic capacitive response of the strain gauge, we adopted a customized data treatment procedure (see Supplementary Note). As shown in Fig. S3 b, the treated data could be fitted perfectly with the simple linear model (regression coefficient ~ 0.9994, slope ~ 1.02). In addition, the curves of loading and unloading overlap (both raw and treated data), indicating that hysteresis is absent in our device.

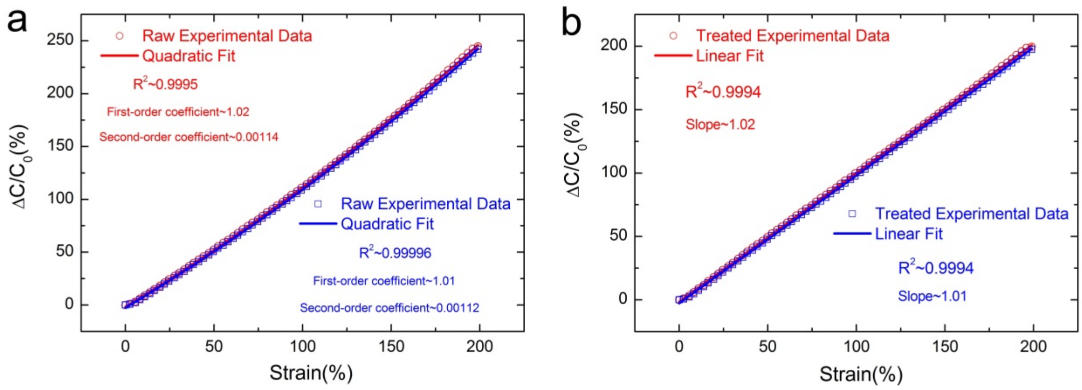

Figure S3. Data treatments. a, Raw data points of a strain test with 200% strain, along with the quadratic fit and the fitting parameters. **b,** Data points after treatments, along with the linear fit and the fitting parameters. **Note:** In both **a** and **b**, the red and blue colors correspond to the data of loading and unloading, respectively.

4. Capacitive response in the strain range of 0-300%

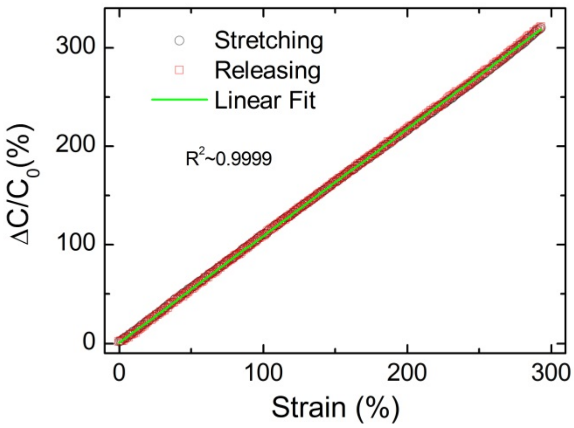

Figure S4. Capacitive response of a strain gauge made from CNT/Dragon skin during both loading (black circles) and unloading (red squares) of a strain of 300%, as well as the linear fit (green line).

The strain gauges made from CNT/Dragon skin could be reversibly stretched to 300% strain and the true capacitive response behaved linearly and uniformly in the entire strain range, as shown in Fig. S4**.** The strain range of 300% is sufficient for most applications and a gauge factor of 1 represents the highest sensitivity of any strain sensors capable of detecting strains larger than 200%. In addition, no hysteresis was observed between the loading and unloading phase, highlighting the deterministic feature of the capacitive sensors. Here, the treated data was shown (see Fig. S3 and Supplementary Note for details).

5. Temperature coefficient of the strain gauge device

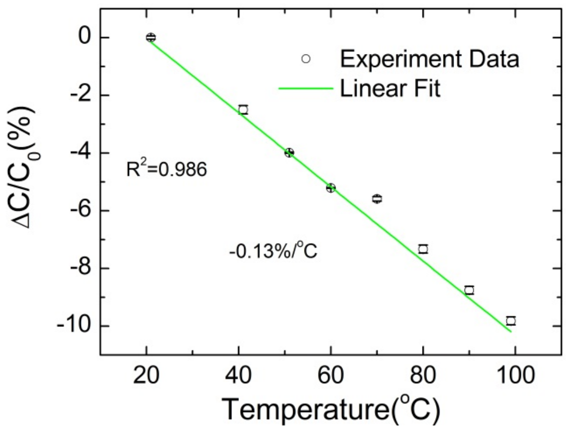

Figure S5. Relative changes in capacitance of a strain gauge as a function of temperature. **Open circles**, data points; **Solid line**, linear fit. Note that the standard errors are almost unnoticeable. The temperature coefficient was estimated to be -0.13%/^{o}C.

Variations in temperature might be detected by the sensor due to thermal expansion effects. We conducted detailed experiments where the environment temperature rose from 20^{o}C to 100^{o}C with a stabilization time of 1 hour for every temperature value. The capacitance of the device was very stable with a temperature coefficient of merely -0.13%/^{o}C. Actually, temperature variations are often characterized by slow drifts and can be compensated by a thermometer.

Supplementary Note: Data treatments procedure.

The raw experimental results, with strains lower than 50%, agreed very well with the theoretical predictions – linear capacitive response with a slope of 1. However, when the applied strain reached 100% or even larger, the capacitive response deviated from linear behavior, following an approximately quadratic relationship with the coefficient of the first-order term very close to 1. The nonlinear behaviors were attributed to the influence of the clamps. The silicone elastomers in the vicinity of the clamps were fixed and would not follow the same Poisson contraction process as the central parts of the sample, leading to a moderately increased total capacitance compared with the undisturbed Poisson capacitor. During the data treatment procedure, the fitted second-order term was subtracted from the raw data, and the remaining part could be regarded as the exact capacitive responses of the undisturbed strain gauges. The modified data could be well fitted by the linear elastic model, with a slope very close to 1, as shown in Supplementary Fig. S3 for the raw and treated data of a test with 200% strain.