Electronic Supplementary Material (ESI) for Nanoscale.

Supporting Information for

A flexible precontact sensor for CNT-Al_2O_3 fibers resistant to extreme temperatures

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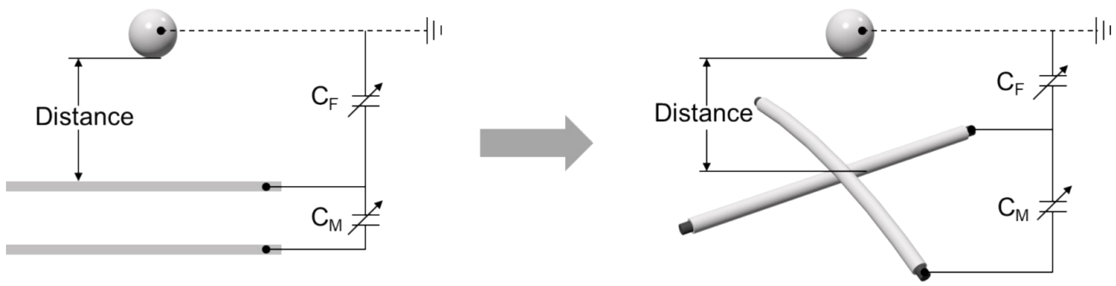

Fig. S1. Principle of precontact sensing. The two crossed CNT-Al_2O_3 coaxial flexible fibers possess the capability to function as a capacitive sensor. This capacitive sensor exhibits a specific precontact detecting capacity. The sensing mechanism is based on two types of capacitance induced by parallel plate capacitance: mutual capacitance between two electrodes (C_M) and self-capacitance to ground (fringing capacitance, C_F). The principle of its operation is similar to other nanomaterial-based fiber sensors that rely on evanescent interaction [1] two crossed fibers, it acts as a third electrode to partially intercept and shunt the edge electric field to the ground within the detectable range. Capacitive coupling of the object to the sensor original reduces the coupling between the two electrodes. The charges on the two electrodes flow out, or the increased electric field directed toward the approaching objects. Therefore, the fringing capacitance C_F increases, and the mutual capacitance C_M decreases logarithmically. This corresponds to the model established by Garbini:

$$C = 4\varepsilon' W \frac{\ln\left(\frac{2H}{h}\right)}{\pi} \quad (1)$$

where W and H are the geometric width and height of the proximity object, h is the distance between the bottom and top electrodes of the fiber, and ε' is a constant factor.

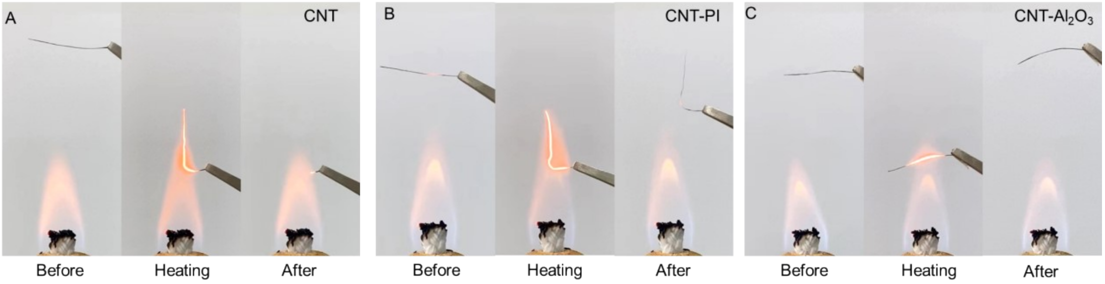

Fig. S2. Short time high temperature resistance testing of CNT, CNT-PI and $CNT-Al_2O_3$. (A) CNT fiber burned at high temperatures for short periods of time. (B) CNT-PI fiber burned at high temperatures for short periods of time. (C) $CNT-Al_2O_3$ fiber burned at high temperatures for short periods of time.

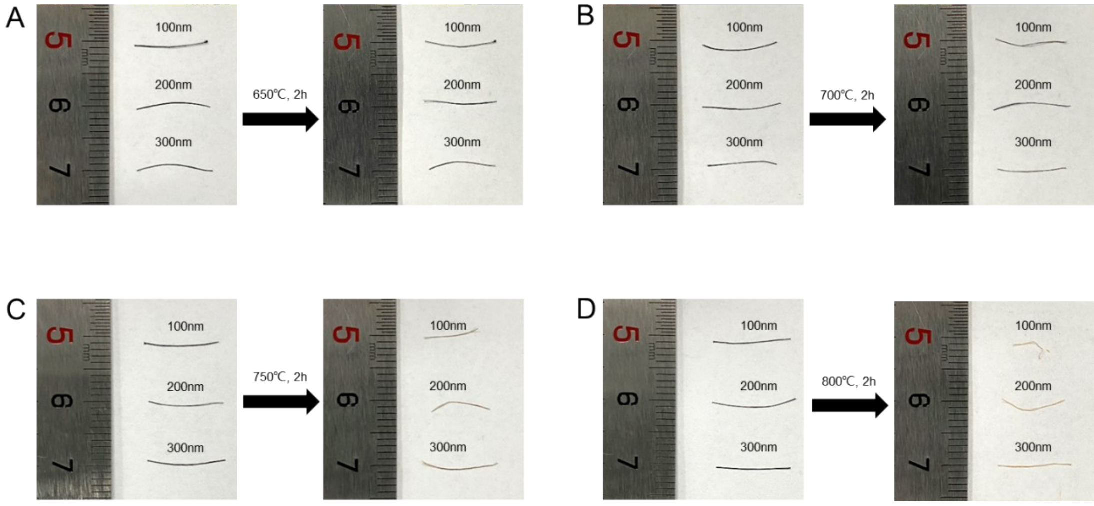

Fig. S3. Long time high temperatures heating of CNT-Al_2O_3 fibers deposited with different thicknesses of Al_2O_3. (A) Before and after the fibers deposited with different thicknesses of Al_2O_3 were exposed to 650 ℃ for 2 hours. (B) Before and after the fibers deposited with different thicknesses of Al_2O_3 were exposed to 700 ℃ for 2 hours. (C) Before and after the fibers deposited with different thicknesses of Al_2O_3 were exposed to 750 ℃ for 2 hours. (D) Before and after the fibers deposited with different thicknesses of Al_2O_3 were exposed to 800 ℃ for 2 hours.

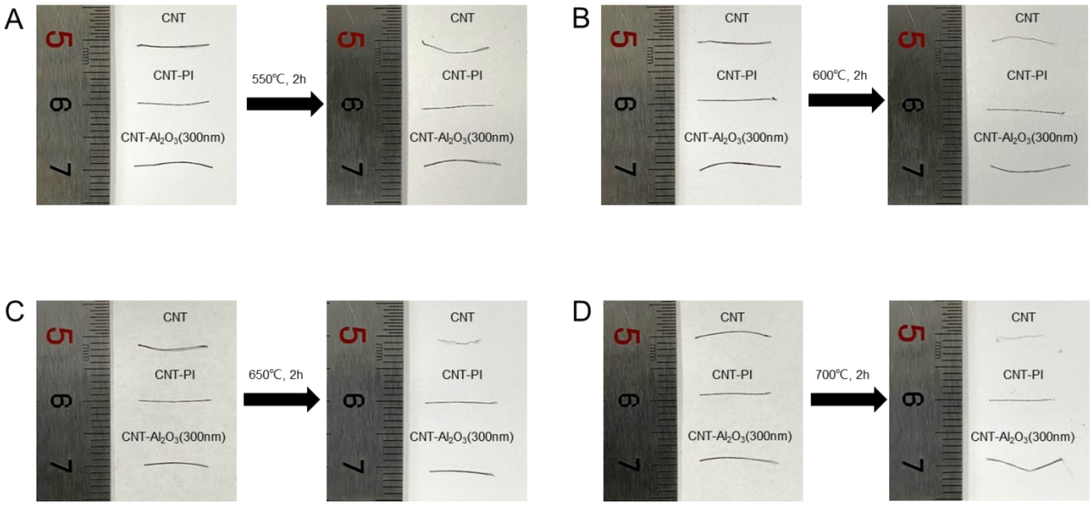

Fig. S4. Long time high temperatures heating of the fibers deposited with different materials. (A) Before and after the CNT, CNT-PI and CNT-Al_2O_3 fibers were exposed to 550 ℃ for 2 hours. (B) Before and after the CNT, CNT-PI and CNT-Al_2O_3 fibers were exposed to 600 ℃ for 2 hours. (C) Before and after the CNT, CNT-PI and CNT-Al_2O_3 fibers were exposed to 650 ℃ for 2 hours. (D) Before and after the CNT, CNT-PI and CNT-Al_2O_3 fibers were exposed to 700 ℃ for 2 hours.

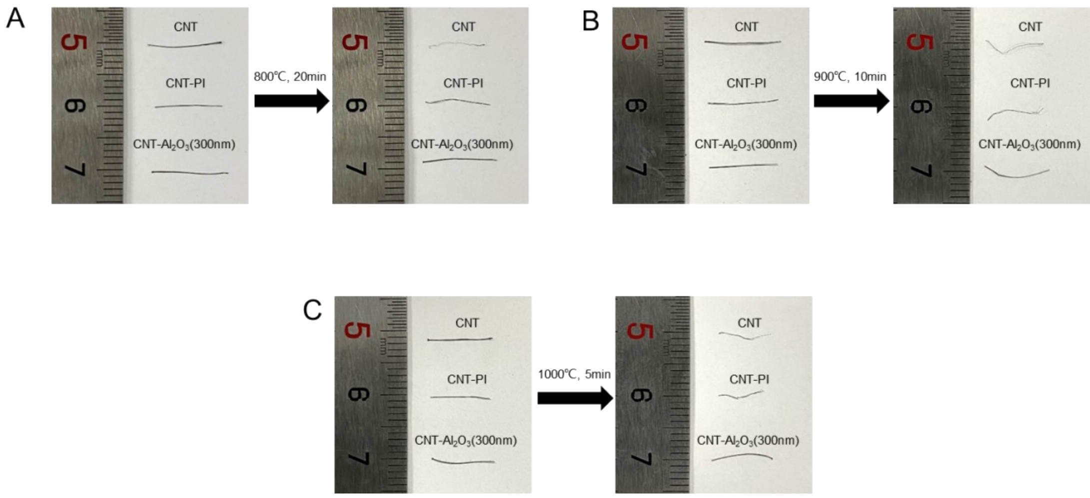

Fig. S5. Short time ultra-high temperatures heating of the fibers deposited with different materials. (A) Before and after the CNT, CNT-PI and CNT-Al_2O_3 fibers were exposed to 800 °C for 20 min. (B) Before and after the CNT, CNT-PI and CNT-Al_2O_3 fibers were exposed to 900 °C for 10 min. (C) Before and after the CNT, CNT-PI and CNT-Al_2O_3 fibers were exposed to 1000 °C for 5 min.

The capacitance-to-distance sensitivity is defined as $S=(\Delta C/C_0)/D$, where ΔC is the capacitance change and D is the distance between the detected object and the sensor. The sensor sensitivity of sensor varies with distance. At the very beginning, from 0 to 5 cm, the capacitance changes sharply with distance. Subsequently, from 5 to 15 cm, the change in capacitance with distance begins to slow down rapidly. After 15 cm, the capacitance basically doesn't change with the distance. The sensor sensitivities for these three stages are 0.02353, 0.00223 and 0.00037 cm^{-1} respectively. The sensor can achieve a resolution of less than 1 mm over an inspection range of 15 cm by using a LCR digital bridge.

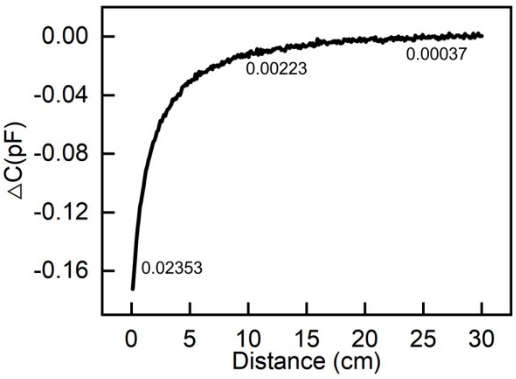

Fig. S6. Distance sensitivity of CNT-Al_2O_3 sensor's sensing.

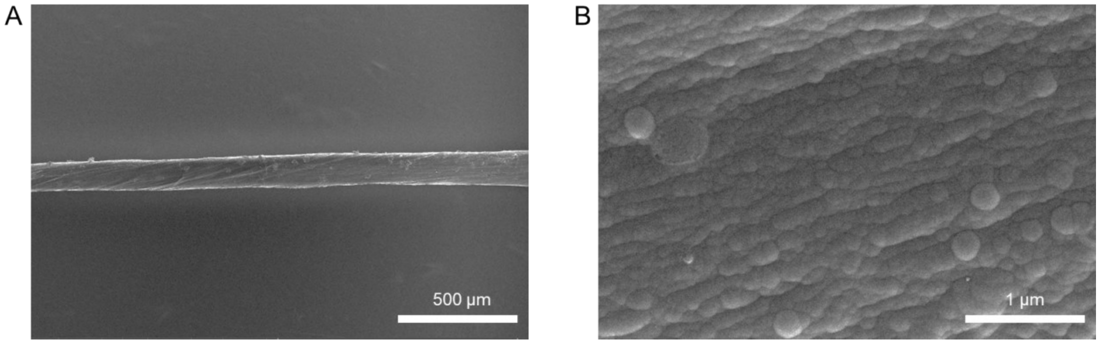

Fig. S7. SEM image of the CNT-Al_2O_3 fiber after bending 10,000 times. (A) SEM image of the CNT-Al_2O_3 fiber after bending 10,000 times. (B) SEM image of the CNT-Al_2O_3 fiber surface after bending 10,000 times.

Table. S1 Comparison of the sensing performance of our work with previously reported work.

Reference	Measuring Distance	Response Strength
Our Work	150 mm	0.16 pF
[2]	55 mm	0.3 pF
[3]	0.14 mm	0.07 pF
[4]	80 mm	150 fF
[5]	160 mm	10 fF
[6]	300 mm	none

Reference:

[1] Wang Y, Li Y, Li Y, Zhang H, Liu Z, Guo Y, et al. Noise canceled graphene-microcavity fiber laser sensor for ultrasensitive gas detection. Pr 2023;11:A1. https://doi.org/10.1364/PRJ.492473.

[2] Huang J, Wang H, Li J, Zhang S, Li H, Ma Z, et al. High-Performance Flexible Capacitive Proximity and Pressure Sensors with Spiral Electrodes for Continuous Human–Machine Interaction 2022:12.

[3] Ruth SRA, Feig VR, Kim M, Khan Y, Phong JK, Bao Z. Flexible Fringe Effect Capacitive Sensors with Simultaneous High-Performance Contact and Non-Contact Sensing Capabilities. Small Structures 2021;2:2000079. https://doi.org/10.1002/sstr.202000079.

[4] Lee H-K, Chang S-I, Yoon E. Dual-Mode Capacitive Proximity Sensor for Robot Application: Implementation of Tactile and Proximity Sensing Capability on a Single Polymer Platform Using Shared Electrodes. IEEE Sensors J 2009;9:1748–55. https://doi.org/10.1109/JSEN.2009.2030660.

[5] Xia F, Campi F, Bahreyni B. Tri-Mode Capacitive Proximity Detection Towards Improved Safety in Industrial Robotics. IEEE Sensors Journal 2018;18:5058–66. https://doi.org/10.1109/JSEN.2018.2832637.

[6] Guan F, Xie Y, Wu H, Meng Y, Shi Y, Gao M, et al. Silver Nanowire–Bacterial Cellulose Composite Fiber-Based Sensor for Highly Sensitive Detection of Pressure and Proximity. ACS Nano 2020;14:15428–39. https://doi.org/10.1021/acsnano.0c06063.