

# DIRECT-WRITE POLYMERIC STRAIN SENSORS WITH ARBITRARY CONTOURS ON FLEXIBLE SUBSTRATES

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## ABSTRACT

Here we demonstrate the direct-write all-polymer nanofibers as uniaxial strain sensors for flexible and wearable devices. Compared to the state-of-art strain sensors, the unique characteristics include: 1) direct-write all polymeric stain sensors for the first time on flexible substrates; 2) local strain sensing with arbitrary contours and designated sensing directions; and 3) 10X higher gauge factor than that of commercial metal strain sensors.

## INTRODUCTION

Flexible and wearable electronics that can be embedded into clothing have drawn increasing interests recently. In such flexible systems, the information on the mechanical deformation has always been an important research topic [1-4]. Conventional strain sensors made of rigid metal or semiconductor materials by means of the piezoresistive effect find rather limited applications in the flexible systems due to their nature brittle properties. One strategy to develop flexible strain sensors is to minimize the strain directly applied on the strain sensors by means of elegant structural designs. For example, buckled ultrathin films made of silicon have high flexibility and stretchability for strain sensing applications [1]. However, the gauge factor of such a strain sensor is low in order for the higher strain sensing range. Furthermore, the mechanical properties of the intrinsically brittle materials are incompatible with those of textiles for integrated systems.

Another approach is to fabricate the sensing devices from soft and flexible materials. Composites composed of polymers and conductive fillers have been demonstrated for this purpose. Such materials can sense mechanical strain by the electron tunneling effect between adjacent particles or by the change in resistance due to the opening and closing of micro-cracks by mechanical deformation [5-11]. These schemes have shown wider strain sensing ranges with similar gauge factors as compared to rigid materials. Furthermore, they can be integrated in textiles with low manufacturing cost. The conductive composites are usually obtained by mixing an insulating polymer with carbon black powders [5-7] or carbon nanotubes [8-11]. In general, these flexible strain sensors are fabricated based on thin film technologies with limited placements and configurations.

This work introduces the direct-write nanofiber composite strain sensors made of the combination of both conductive and insulating polymers. The all-polymer material is intrinsically flexible and easy to process and the 1D nanostructures are easy to adapt to arbitrary contours to sense local deformation in the designated direction. Furthermore, the MEMS-compatible process

enables its direct integration with various wearable devices, such as gloves, textiles and clothes.

## WORKING PRINCIPLE

### Strain Induced Resistance Change

The nanofiber described in this work contains two types of molecule chains, in which the conductive polymer chains form a network for electrical conduction over the insulating polymer. Here we use polypyrrole (PPy) as the conductive component and polyethylene oxide (PEO) as the insulating one, as illustrated in Figure 1a. Figure 1b explains the working principle of strain sensing at the molecule level. When the composite material is stretched or compressed, the electron conduction path starts altering, resulting in resistivity increase or decrease. Combined with geometry variation of the fiber, resistance changes corresponding to applied strain can be measured.

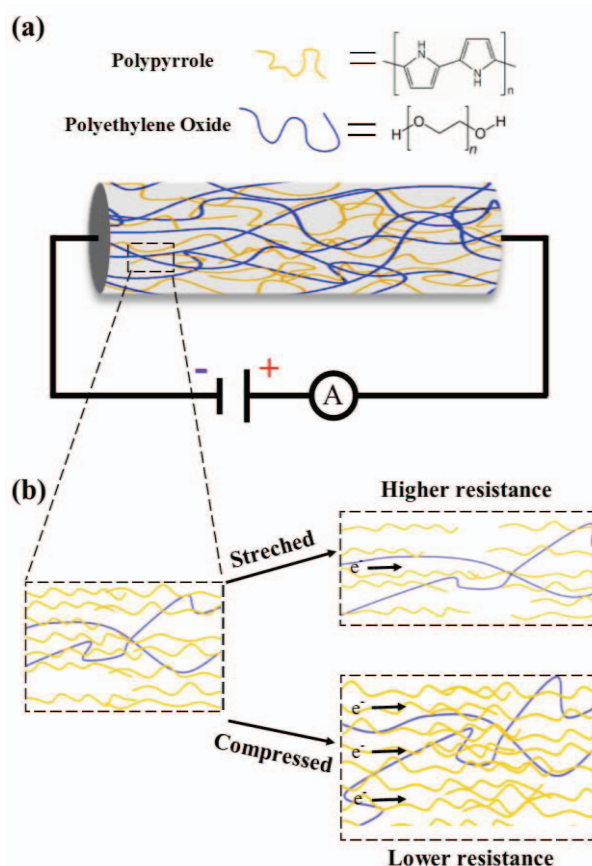


Figure 1: Schematics: (a) a nanofiber consisting of conductive and nonconductive polymer; (b) fiber resistance changes as conductive percolation network changes under deformation.

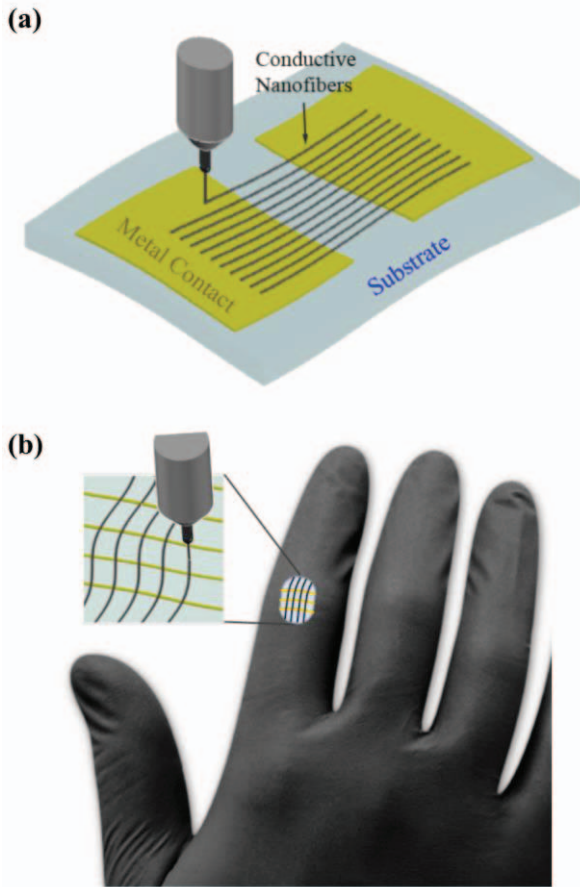


Figure 2: Schematics: (a) direct writing of nanofibers across two metal contact pads via near-field electrospinning; (b) possible application of direct-write sensors of arbitrary contours on wearable devices.

### Direct-write Process

The direct-write nanofibers described above can be produced by the near-field electrospinning process [12], as illustrated in Figure 2a. The polymer solution is loaded in a syringe. By placing the syringe tip several millimeters above the substrate and connecting the needle to a high voltage supply of about 1kV, polymer solution is ejected from the tip and forms nanofibers. Aligned nanofibers can thus be directly written on the collector by either moving the syringe or substrate in a controllable manner. This process can also produce arbitrary contours on wearable surfaces by placing and controlling the tip in the three dimensional space, as illustrated in Figure 2b.

## DEVICE FABRICATION

### Material Synthesis

Intrinsically conductive polymers are usually not soluble in common solvents. We synthesize a soluble PPy by doping it with a docusate salt, which has long chains that reduce interchain interactions to increase solubility [13]. In a typical process, 8.05g pyrrole monomer and 26.67g docusate sodium salt as the dopant are mixed in 180mL deionized water to make the solution A. On the other hand, 4.01g ammonium persulfate as the oxidant is dissolved in 20mL deionized water to make the solution B. Both solutions are cooled down to 0°C and then mixed together. The reaction is kept at 0°C under vigorous stirring for 24h. The PPy product is insoluble in water and becomes precipitate. The precipitate is then filtered, washed by methanol and water for several times, and dried under vacuum for 12h. Dried PPy powder is finally dissolved in dimethylformamide (DMF) to make 8wt% solution.

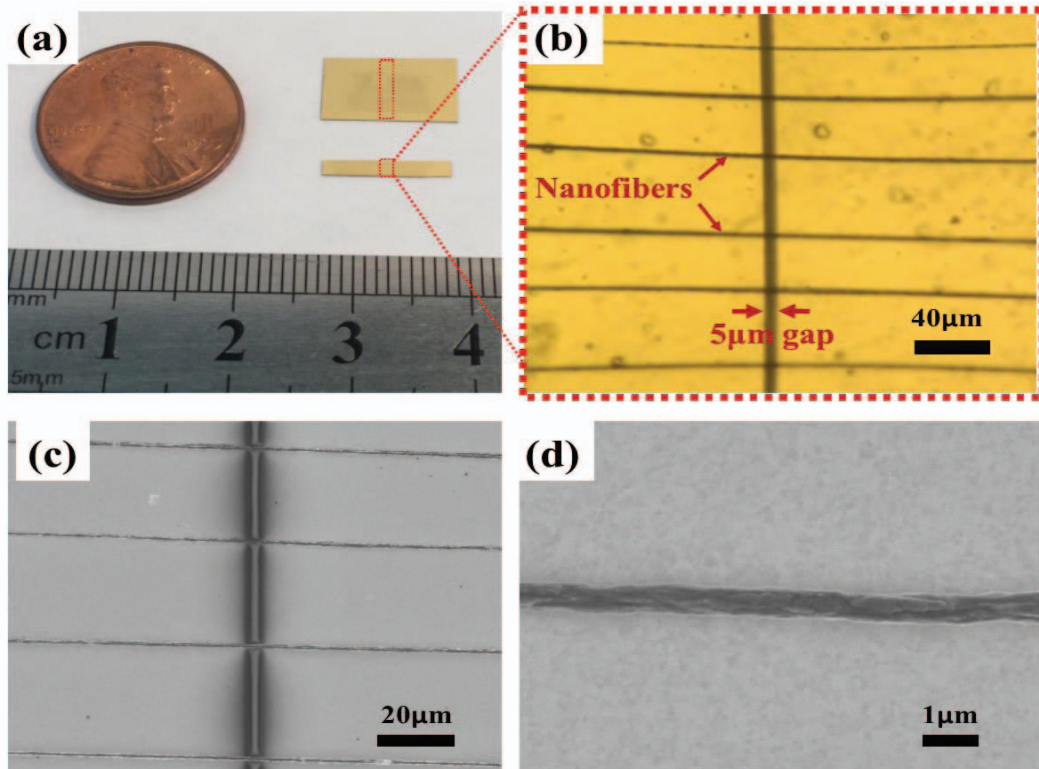


Figure 3: (a) An optical photo showing prototype sensors and a one-cent US coin. (b) Aligned nanofibers on two gold electrodes with a 5μm gap in between. (c, d) SEM images of nanofiber strain sensors.

Nonconductive PEO (Mw=5,000,000) is supplied by Sigma-Aldrich. It is dissolved in a mixed solvent (DMF: Acetone=2:3) to make 2wt% solution. PPy solution is then mixed with PEO solution so that the weight ratio of PPy and PEO is 1:1.

### Prototype Preparation

A flexible substrate film with metal contacts is first prepared for the prototype. A carbon fiber with a diameter of 7 $\mu$ m serving as a shadow mask is attached on a piece of 127 $\mu$ m-thick Kapton® polyimide film. Then a layer of 100nm-thick gold is deposited onto the film by thermal evaporation. The carbon fiber is then removed, and a gap of about 5 $\mu$ m-wide which separates two gold pads is left on the film. The substrate is attached on a grounded silicon wafer for the following process.

The mixed polymer solution described above is loaded in a syringe with a flat stainless steel tip. The tip is connected to a high voltage source and placed 3mm above the substrate. A voltage around 0.9kV will start the electrospinning process to eject nanofibers of PPy/PEO from the tip and write them onto the substrate.

Figure 3a shows a photo of two prototypes compared with a US coin. The substrate is cut into pieces of arbitrary size to make it easy to handle and test, and aligned nanofibers with diameters from 400-700nm are written within the small area in the middle. Figures 2b-d show a magnified optical photo and SEM images of the nanofibers. The minimum required area for strain sensing is quite small, since one nanofiber across the 5 $\mu$ m gap would work. Here we use the multiple- and aligned-fiber arrangements to help enhance the signal strength and reduce the detection variations for better sensing results.

## RESULTS AND DISCUSSION

Experimentally, we have deformed the prototype substrate upwards to apply tensile stress and downward to apply compressive stress on the nanofibers. Strain is calculated by the thickness of the substrate (127 $\mu$ m) divided by the bending radius. The I-V characteristics of

the prototypes are recorded by a Gamry Reference 600 potentiostat, and the resistances are calculated from the corresponding curves.

Figure 4a plots the typical I-V curves of a prototype sensor with 100 nanofibers under tensile, compressive, and no strains. The straight lines in I-V curves indicate that the sensor works as a resistor and changes resistance under different strains. A resistance of 16k $\Omega$  is calculated when the device is under no strain and the contribution from the metal layer can be neglected since the resistance of the gold layer is only about 1 $\Omega$  per square.

Figure 4b plots the relative resistance change as a function of applied strain in the direction parallel or perpendicular to the nanofibers. It is clear that the strain sensor is uniaxial – it is only sensitive to the applied strain direction parallel to the nanofibers. The curve also shows that the resistance is almost linearly dependent on the applied strain. Furthermore, a gauge factor (relative resistance change divided by strain) of 15 is calculated from the slope of the linear fit, which is an order of magnitude higher than that of commercial strain gauges and much higher than values from composites using carbon nanotube networks [8-11].

To demonstrate its application in wearable systems, we attach a prototype sensor on a glove (Figures 5a and c). The real-time current under a DC bias of 0.1V is recorded in Figures 5b and d, for different magnitude and frequency of finger movements. When the finger bends down, the nanofibers are under tensile strain with smaller measured current. The relative change of current corresponds to the bending magnitude of the finger. Therefore, Figures 5b and 5d correspond to fast-small and slow-large movements, respectively. This experiment also shows that the sensor responds fast enough (less than 0.1s) to human body movement, and it recovers back to its original states from multiple bending cycles.

## CONCLUSIONS

This paper demonstrates uniaxial strain sensors for wearable devices by using conductive polymer

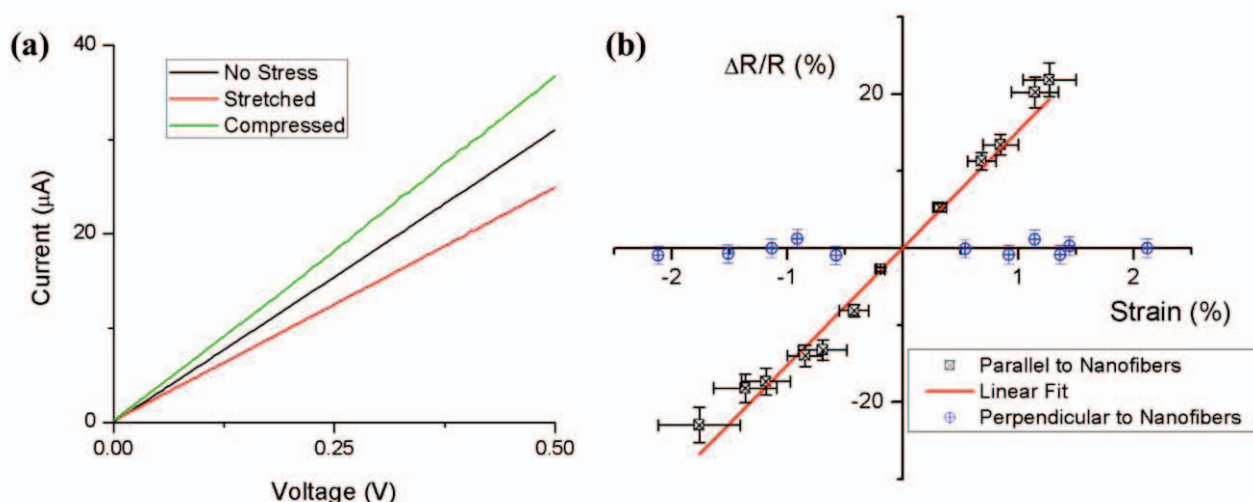


Figure 4: (a) Measured I-V curves of a nanofiber sensor without applied deformation (black line); stretched (red line); and compressed (green line). (b) Relative resistance change with respect to applied strain of the nanofibers sensor with the applied strain in the same and perpendicular direction of the nanofibers.



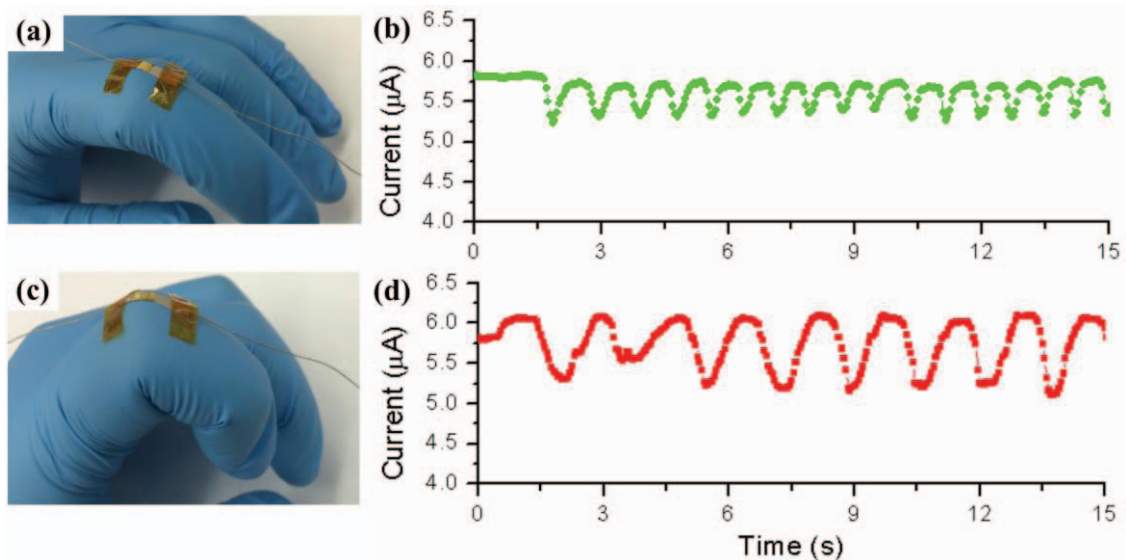


Figure 5: (a) and (b): the optical photo and real-time testing result showing a prototype sensor on a glove with small back and forth bending of a human finger, respectively. (c) and (d): the optical photo and real-time testing result showing a prototype sensor on a glove with large bending of a human finger, respectively. A constant voltage of 0.1V is applied in both tests, and the current is recorded by a galvanometer.

nanofibers. We synthesize soluble PPy and prepare direct-write PPy/PEO composite nanofibers by the near-field electrospinning process. Experiments show that the nanofibers are exclusively sensitive to strain applied along the fiber direction. A gauge factor of 15 is calculated from the prototype. We further demonstrate that the sensor can be attached on wearable devices like gloves to detect human motions. Since the process of the nanofiber is MEMS-compatible, we believe the sensor can be integrated with other flexible micro systems in the future.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] D. Y. Khang, et al., "A stretchable form of single-crystal silicon for high-performance electronics on rubber substrates," *Science*, vol. 311, no. 5758, pp. 208–212, 2006.
- [2] D. H. Kim, et al., "Stretchable and foldable silicon integrated circuits," *Science*, vol. 320, no. 5875, pp. 507–511, 2008.
- [3] D. H. Kim, and J. A. Rogers, "Stretchable electronics: materials strategies and devices," *Advanced Materials*, vol. 20, no. 24, pp. 4887–4892, 2008.
- [4] R. Bogue, "Nanomaterials for new and emerging physical sensing applications: a review of recent developments," *Sensor Review*, vol. 35, no. 4, pp. 321–328, 2015.
- [5] C. Cochrane, V. Koncar, M. Lewandowski, and C. Dufour, "Design and Development of a Flexible Strain Sensor for Textile Structures Based on a Conductive Polymer Composite," *Sensors*, vol. 7, no. 4, pp. 473–492, 2007.
- [6] C. Mattmann, F. Clemens, and G. Tröster, "Sensor for Measuring Strain in Textile," *Sensors*, vol. 8, no. 6, pp. 3719–3732, 2008.
- [7] M. Knite, V. Teteris, A. Kiploka, and J. Kaupuzs, "Polyisoprene-carbon black nanocomposites as tensile strain and pressure sensor materials," *Sensors Actuators, A Phys.*, vol. 110, no. 1–3, pp. 142–149, 2004.
- [8] T. Yamada, Y. Hayamizu, Y. Yamamoto, Y. Yomogida, A. Izadi-Najafabadi, D. N. Futaba, and K. Hata, "A stretchable carbon nanotube strain sensor for human-motion detection," *Nat. Nanotechnol.*, vol. 6, no. 5, pp. 296–301, 2011.
- [9] D. J. Lipomi, M. Vosgueritchian, B. C.-K. Tee, S. L. Hellstrom, J. A. Lee, C. H. Fox, and Z. Bao, "Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes," *Nat. Nanotechnol.*, vol. 6, no. 12, pp. 788–792, 2011.
- [10] M. Amjadi and I. Park, "Carbon nanotubes-ecoflex nanocomposite for strain sensing with ultra-high stretchability," *IEEE MEMS*, pp. 744–747, 2015.
- [11] N. Hu, Y. Karube, M. Arai, T. Watanabe, C. Yan, Y. Li, Y. Liu, and H. Fukunaga, "Investigation on sensitivity of a polymer/carbon nanotube composite strain sensor," *Carbon N. Y.*, vol. 48, no. 3, pp. 680–687, 2010.
- [12] D. Sun, C. Chang, S. Li, and L. Lin, "Near-Field Electrospinning," *Nano Lett.*, vol. 6, no. 4, pp. 839–842, 2006.
- [13] E. J. Oh, K. S. Jang, and A. G. Macdiarmid, "High molecular weight soluble polypyrrole," *Synthetic Metals*, vol. 125, pp. 267–272, 2002.

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