Supporting Information

High performance electronic devices based on nanofibers via crosslinking welding process

Youchao Cui,[a,b,c†] You Meng,[a,b,c†] Zhen Wang,[a,b,c] Guoxia Liu,[a,b,c,d*] Rodrigo Martins,[e] Elvira Fortunato,[e] and Fukai Shan[a,b,c,d*]

[a]College of Physics, Qingdao University, Qingdao 266071, China

[b]College of Microtechnology & Nanotechnology, Qingdao University, Qingdao 266071, China

[c]State Key Laboratory for Biological Polysaccharide Fiber and Ecological Textiles, Qingdao University, Qingdao 266071, China

[d]Collaborative Innovation Center for Eco-Textiles of Shandong Province, Qingdao 266071, China

[e]Department of Materials Science, Universidade Nova de Lisboa, Campus de Caparica, Caparica

Experimental section

In a traditional procedure, 0.2 g anhydrous indium chloride ($InCl_3$, 99.999%, Aladdin) was mixed with 2.0 g polyvinyl pyrrolidone (PVP, Mw=1 300 000, Aladdin) and 10 ml N,N-Dimethylformamide (DMF, 99.9%, Aladdin). Mixed solutions with various weight ratios of PVP to amine-hardened epoxy resin (P/E), ranging from 10/0, 10/1, 10/2 to 10/5, were used to prepare the precursor solutions for electrospinning. After persistent stirring for 12 h at room temperature, the transparent and viscous solutions were obtained. Using a syringe pump, the precursor solutions were pushed into the needle with an inner diameter of 0.34 mm at a constant flow rate of 0.5 ml/h. A piece of flat aluminum foil was placed 15 cm away from the tip of the needle to collect the nanofibers. The cleaned thermally-grown 100 nm-thick SiO_2/Si wafers were adhered to the flat aluminum foil. Upon applying a DC voltage of 15 kV on the metal needle, a bending unstable fluid jet was ejected from the tip. The solvent evaporated and randomly oriented nanofibers were spun on the collector. Then the nanofibers were baked at 150 ^{o}C on hot plate for 10 min to promote crosslinking welding reaction.

To integrate the FETs based on welded In_2O_3 nanofibers, the nanofibers were electrospun from the precursor solution with P/E of 10/2. The FETs channels with various nanofiber densities were prepared by varying the nanofiber collection time during the electrospinning. The nanofiber density was calculated from the number of nanofibers bridging the source and drain electrodes divided by the width of electrodes. Subsequently those samples were calcined at 500 ^{o}C in atmosphere for 120 minutes to remove organic components. Finally, Al source and drain electrodes were deposited by thermal evaporation using shadow mask. The channel length and width were 250 and 1000 μm, respectively.

To integrate the In_2O_3 FETs based on high-k dielectric, thermally-grown SiO_2 dielectrics were substituted by solution-processed ZrO_x thin films. 0.15 M ZrO_2 precursor solution was prepared by dissolving zirconium nitrate ($Zr(NO_3)_4 \bullet 5H_2O$, AR, Macklin) in 2-methoxyethanol (2-ME, 99.9%, Aladdin). The precursor solution was stirred for 12 h before spin-coating. Heavily-doped p-type silicon substrates were cleaned ultrasonically in acetone, ethanol, and deionized water sequentially and dried by N_2 gun. The ZrO_x precursor solution was filtered through a 0.22-μm polytetrafluoroethylene (PTFE) syringe filter and then spin coated on Si substrate at a speed of 500 rpm for 3 s and 5000 rpm for 25 s. The samples were baked at 150 ^{o}C on a hot plate for 10 min to cure the thin film and then thermal annealed at 600 ^{o}C for 120 minutes.

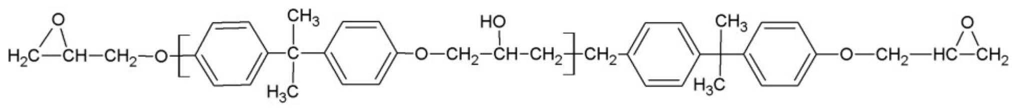
Characterization methods. The microstructure of the nanofibers was measured by scanning electron microscopy (SEM, S-4800, Hitachi). The electrical properties of the FETs were investigated using a semiconductor parameter analyzer (2634B, Keithley) under ambient conditions in a dark box. The subthreshold value (SS) is given by the following equation:

$$SS = \left[\frac{dlog(I_{DS})}{dV_{GS}}\right]^{-1}$$

The μ_{FE} was extracted from the following equation:

$$I_{DS} = \frac{1W}{2\,L}\mu_{FE}C_i(V_{GS} - V_{TH})^2$$

where V_{GS} is the gate voltage, W and L are the channel width and length, respectively. The threshold voltage (V_{TH}) was calculated from the linear portion of $(IDS)^{1/2}$ vs VGS. The areal capacitance (C_i) was directly measured via a parallel-plate capacitance model, which was widely applied in calculating the field-effect mobility of traditional thin film transistors. The areal capacitance (i.e., the capacitance per unit area) was calculated from the value of the measured capacitance (F) divided by the electrode area (1.5 mm^2). It is worth noting that the parallel-plate capacitance model overestimates the actual gate capacitance and underestimates the mobility of the nanofibers-based devices.[1]


(a)

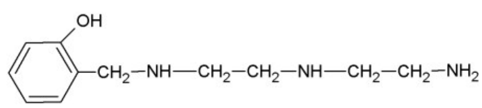

(b)

Fig. S1 Chemical structure of (a) BADGE and (b) Mannich base.

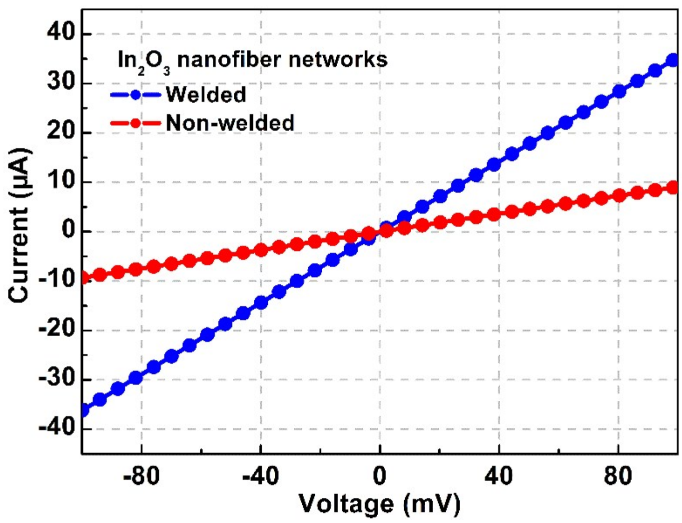


Fig. S2 I−V characteristics of welded and non-welded In_2O_3 NFNs.

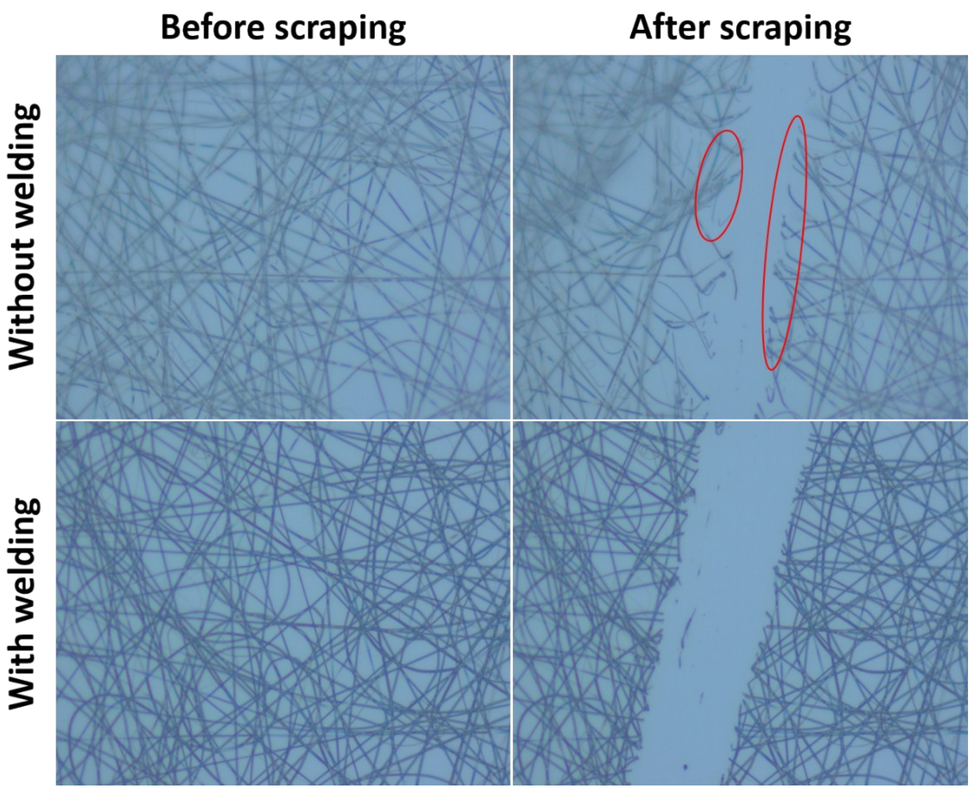


Fig. S3 Scraping tests of NFNs with welding and without welding.

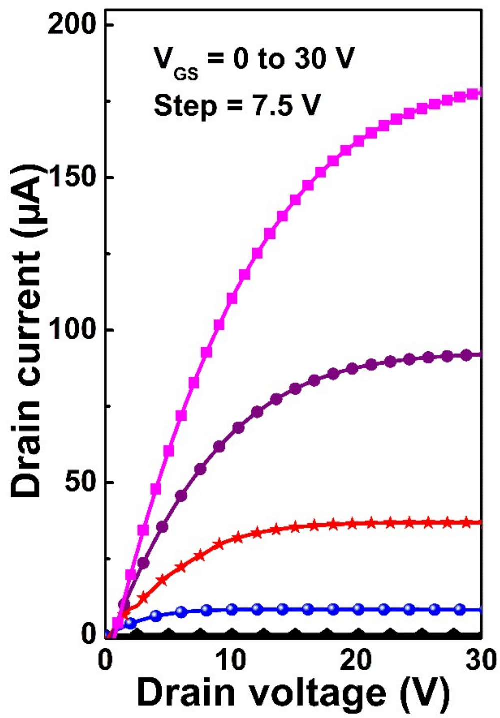


Fig. S4 Output characteristics of FETs based on welded In_2O_3 NFNs/SiO_2 with nanofiber density of 0.4 μm^{-1}.

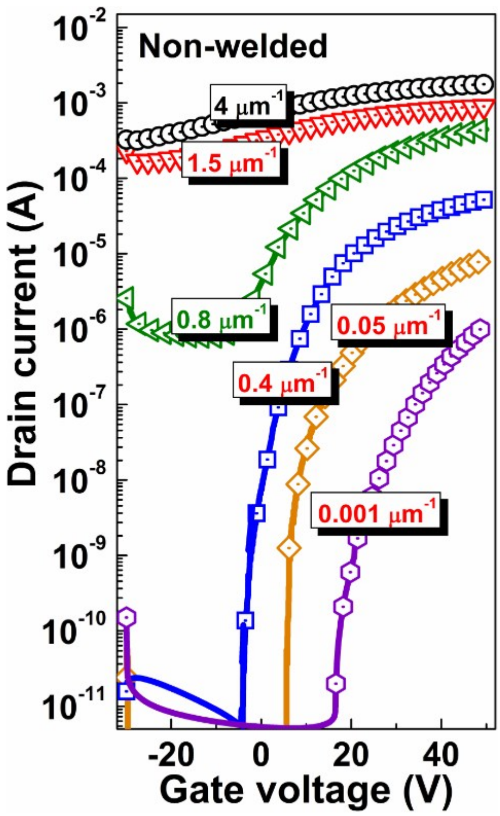


Fig. S5 Transfer curves of FETs based on non-welded In_2O_3 NFNs/SiO_2 with various nanofiber densities (0.001 μm^{-1}, 0.05 μm^{-1}, 0.4 μm^{-1}, 0.8 μm^{-1}, 1.5 μm^{-1} and 4 μm^{-1}).

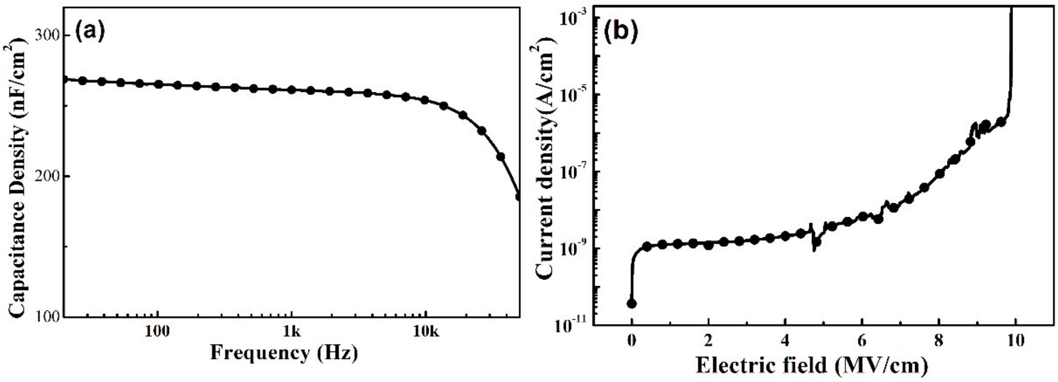


Fig. S6 (a) Capacitance density of solution-processed ZrO_x dielectric thin films as a function of the frequency. (b) The leakage-current density vs electric field.

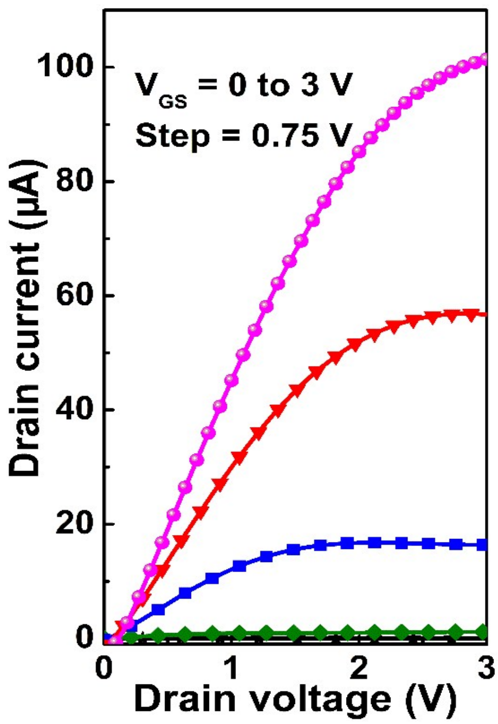


Fig. S7 Output characteristics of FETs based on welded In_2O_3 NFNs/ZrO_x with nanofiber density of 0.4 μm^{-1}.

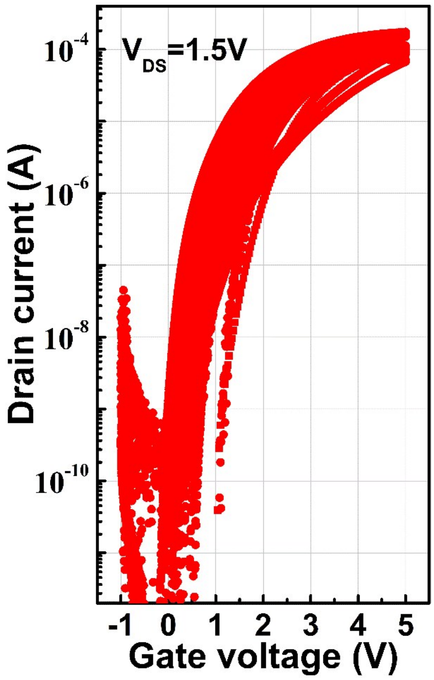


Fig. S8 Transfer curves of FETs based on welded In_2O_3 NFNs (5×5 array) at V_{DS} of 1.5 V with nanofiber density of 0.4 μm^{-1}.

Table S1. Corresponding performance parameters of FETs based on In_2O_3 NFNs with various nanofiber densities.

	Fiber Density (μm^{-1})	μ_{FE} (cm^2 V^{-1} s^{-1})	V_{TH} (V)	$I_{on/off}$	SS (V dec^{-1})
Welded	0.01	0.04	33	1*10^5	3
	0.05	0.12	26	5*10^5	2.7
	0.4	3.50	3	6*10^7	2
	0.8	3.70	-10	1.2*10^4	4.5
	1.5	4.77	-35	-	-
	4	6.64	-45	-	-
Non-welded	0.001	0.04	34	1*10^5	3.2
	0.05	0.11	27	5*10^5	3
	0.4	0.70	3	5*10^6	1.9
	0.8	0.93	-10	7*10^2	7
	1.5	1.22	-20	-	-
	4	1.87	-30	-	-

References

1. S. Chae, W. Yu, J. Bae, D. Duong, D. Perello, H. Jeong, Q. Ta, T. Ly, Q. Vu, M. Yun, X. Duan, Y. Lee, *Nat. Mater.,* 2013, ***12***, 403-409.