Chip on a fiber toward the e-textile computing platform

Sunbin Hwang

Korea Institute of Science and Technology

Minji Kang

Jeonbuk National University <https://orcid.org/0000-0001-6244-4625>

Aram Lee

Korea Institute of Science and Technology

Sukang Bae

Korea Institute of Science and Technology

Seoung-Ki Lee

Korea Institute of Science and Technology

Sang Hyun Lee

Chonnam National University

Takhee Lee

Seoul National University <https://orcid.org/0000-0001-5988-5219>

Gunuk Wang

Korea University <https://orcid.org/0000-0001-6059-0530>

Tae-Wook Kim (✉ twk@jbnu.ac.kr)

Jeonbuk National University <https://orcid.org/0000-0003-2157-732X>

Article

Keywords: E-Textiles, Wearable electronics, Transistors, Photodetectors, Temperature sensors

Posted Date: October 9th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-85927/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Electronic textiles have been considered one of the desired device platforms due to their dimensional compatibility with fabrics by weaving them with yarn. However, the existing electronic textile platforms are generally composed of only one type of electronic component with a single function on a fiber substrate because of processing challenges. A precise connecting process between each electronic fiber is essential to configure the desired electronic circuits or systems. Here we present a chip on a fiber, a new electronic fiber platform, by introducing large scale integration of electronic device or circuit components onto a one-dimensional microfiber substrate. The electronic components such as transistors, inverters, ring oscillators, and thermocouples were integrated together onto the outer surface of a fiber substrate with precise semiconductor and electrode patterns. Our results show that the electronic components can be integrated on a single fiber with reliable operation. We evaluate the electronic properties of the chip on a fiber as a multifunctional electronic textile platform by testing their switching and data processing, as well as sensing or transducing units for detecting optical/thermal signals. The demonstration of the chip on a fiber suggests significant proof of concepts for realization of high performance with wearable electronic textile systems.

Main Text

Fiber electronics are of considerable interest for wearable applications and smart textiles, which can facilitate communication and the interaction between humans and their surroundings¹⁻³. As a basic element of functional textiles, the one-dimensional (1D) form of the thread-like fibers offers high flexibility, isotropic deformations, breathability, and lightweight in fabric structure^{4,5}. The 1D functional fibers can be further processed into two-dimensional (2D) textiles and three-dimensional yarn configurations through traditional textile engineering techniques, such as twisting, weaving, sewing, knitting, knotting, interlacing, etc^{5,6}. Owing to such intrinsic merits, in recent years, fiber-based device components that perform optoelectronic functions, such as health/environmental monitoring, displays, sensing, energy harvesting, energy-storing, electromagnetic shielding, and information processing, have been integrated directly into fabrics to demonstrate futuristic clothes⁷⁻¹⁴.

However, the existing electronic fiber platforms are generally composed of only one type of electronic component with a single function on a fiber substrate that is attributed to the all-around wrapping of an active layer on the fiber without any patterning. A precise connecting process between each electronic fiber is also essential to configure the desired electronic circuits or systems into the 2D textile while minimizing the degradation of the device performance¹⁵. Although those functional fiber assemblies can be used for computing, recording, detecting, and readout of data sequentially similar to conventional integrated circuits and multifunctional devices on 2D wafers, both limitations on scaling down and difficulty on the configuration of the electronic circuit still remain as major obstacles for the implementation of practical electronic fiber system. First, numerous complex and functional connections are generated from large scale integration, and thus reducing wiring, such as conductive threads, is

considered a bottleneck for further development. Second, the areal density of the device should be increased by introducing a specifically designed architecture or process¹⁶. In this point of view, it is highly necessary to develop compact and miniaturized electronic systems that are capable of working on a single fiber. Nevertheless, to date, a new strategy on the fabrication of a high-density electronic fiber possessing multiple electronic components and circuits as well as maintaining excellent electrical performance under mechanical strain has not yet been reported.

In this work, we present a new electronic fiber platform that enables large scale integration (LSI) of electronic device components on the surface of a 1D fiber substrate with a diameter of 150 μm (see Fig. 1A). By using high-resolution maskless photolithography with a capillary tube assisted coating method¹⁷, multiple miniaturized device units are integrated onto a very narrow and thin fiber surface. As a proof-of-concept demonstration, basic electronic devices (field-effect transistors, inverters, and ring oscillators) and sensors (photodetectors, signal transducers, and distributed temperature sensors consisting of thermocouples) are fabricated onto the two different sides of the rectangular fiber, respectively. The chip on a fiber exhibits various electronic functions (UV detection and switching electrical signals in a single transistor, symmetric input/output behavior in the n-type inverter, oscillation characteristics of 5-stage ring oscillator) and thermal sensing performance with high mechanical stability. We believe that our approach is one of the big steps necessary to implement high-density electronic fiber platforms for wearable electronic textiles.

The integrated circuit on a fiber system, illustrated in Figs. 1A and B, consists of two different electronic parts: basic optoelectronic elements and a temperature sensor. A square-shaped microfiber made of fused silica was employed as a transparent and flexible substrate because the cuboid shape includes six planar faces in three axes, enabling higher integrated density. A transistor, a capacitor, an inverter, and a ring oscillator based on an indium gallium zinc oxide (IGZO) metal oxide semiconductor are placed on the top surface of the fiber while the temperature sensor is built onto the side of the fiber. To demonstrate the whole device, we exploited both a capillary tube-assisted coating (CTAC) method and high-resolution maskless photolithography, which are able to fabricate precisely patterned metal electrodes onto the thin and narrow monofilament fiber substrate^{17,18}. The CTAC process has the potential to be compatible with a reel-to-reel coating process, which is an efficient way to minimize material waste and allows fine control of photoresist (PR) film thickness and uniformity by adjusting the coating speed and solution concentration¹⁷. Cross-sectional scanning electron microscope (SEM) images indicate that the CTAC-processed PR film uniformly covered the entire outer surface of the fiber, and the thickness of the PR layer is estimated to be approximately 2 μm (Supplementary Figure S1). After coating and baking the PR film on the fiber, a laser pattern generator was employed to quickly expose the PR layer along with the electrode pattern (Supplementary Fig. S1). The maskless lithography directly transfers the design patterns onto the fiber substrate without utilizing a photomask, and enables sophisticated electrode patterning for the fabrication of various electronic fiber devices, as shown in Supplementary Fig. S2¹⁸. Experimental details (the deposition of metal thin films and wet-etching through the photolithography) and the electrode patterns formed on the fiber are also described in Supplementary Fig. S3. Figures 1C

and 1D show a SEM image and a photograph of the entire device fabricated on the flexible fiber substrate.

Optical microscopic images and circuit diagrams of each electrical device are shown in Figures 2A and 2D, respectively. A field-effect transistor (FET), a basic device element, in top-gate and bottom-contact (TG/BC) structure was fabricated to verify the capabilities of the miniaturized devices for electronic fiber applications. IGZO and Al_2O_3 are used as an amorphous oxide semiconductor and a gate dielectric, respectively. Their chemical composition was analyzed with X-ray photoelectron spectroscopy (XPS), and the dielectric capacitance of the 15-nm-thick Al_2O_3 layer was measured as 180 nF cm^{-2} , as described in Supplementary Fig. S4. Figure 2B shows the transfer characteristics of the driver FET in the depletion-load *n*-type metal-oxide-semiconductor (*n*-MOS) inverter. The IGZO-based FET exhibits field-effect mobility of $5.5 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ in the saturation regime with negligible hysteresis and an On/Off current ratio greater than 10^7 at a gate-source voltage (V_G) of 5 V and a low drain-source voltage (V_D) of 5 V. These values are similar to that of previously reported IGZO-based FETs, indicating good reproducibility and validity of this fabrication process for chip on a fiber applications^{19–22}.

Based on the IGZO FETs, the electrical characteristics of both an inverter and a five-stage ring oscillator on the fiber substrate were evaluated, as shown in Figs. 2C, 2E, and 2F. The depletion-load *n*-MOS inverter was implemented by a series connection between two *n*-MOS transistors, which play the role of driver and load, respectively. The source electrode of the load transistor is connected to the gate electrode of the load transistor and the drain electrode of the driver transistor. A channel width (W) of 20 μm and 50 μm with the same channel length (L) of 10 μm for the driver and load components were used, respectively, for the proper balance between the driver and load transistors for the operation of the inverter and the ring oscillator. The voltage transfer curve is measured for a bias voltage (V_{bias}) of 5 V and supply voltages (V_{DD}) of 2 V to 5 V. The output voltage-input voltage ($V_{\text{Out}}-V_{\text{In}}$) of the *n*-MOS depletion load inverter can be seen in Fig. 2C. Subsequently, the five-stage ring oscillator was prepared by the depletion-load *n*-MOS inverter having IGZO channels as described above. The ring oscillator is connected in series with five depletion-load *n*-MOS inverters. The 1st inverter output becomes the 2nd inverter input and the output of the 2nd inverter becomes the 3rd inverter input. This chain continues to the 5th inverter, and finally, the output of the last (5th) inverter returns to the input of the primary (1st) inverter (See Figure 2D). In this way, integrated circuits (IC) were successfully fabricated using conventional semiconductor processes on a flexible monofilament fiber substrate. Although a higher process level and optimization for more refinement and accuracy are still required, it will be possible to integrate more complex ICs on the side of facets of rectangular fibers or the surface of a cylindrical fiber. In addition, the output voltage waveform ($V_{\text{out}}\text{-time}$), oscillation frequency (f), and propagation delay (τ) of the five-stage ring oscillator in according to an increase in power supply voltage (V_{DD}) are described in Figs. 2E and 2F. The τ of the switching events was determined from fitting exponential functions to the measured V_{out} transitions that depend on the supply voltage. On increasing V_{DD} , the τ increased and the f decreased. To test the flexibility and stability of the chip on a fiber, the IGZO FET device on the fiber was measured under both

tensile and compressive stress conditions, as can be seen in Figs. 2G and 2H. For systemic analysis of the IGZO FET on the fiber under various stress conditions, the electronic fiber was placed and fixed on flexible polyethylene terephthalate (PET) substrates. The electrical parameters such as field-effect mobility, threshold voltage, and drain current of the IGZO FET on the fiber were well maintained for its switching performances up to a compressive strain of 0.64% and a tensile strain of 0.68%, respectively. Although these mechanical conditions are not fully harsh compared to conventional flexible electronic devices, we believe that the chip on a fiber platform is still considered as one of the valid approaches for wearable monofilament computing systems.

To explore the possibility of multifunctional device integration on a fiber, we monitored the electrical signals of the sensor on a fiber against changes of both UV light and temperature. The UV-light and temperature sensors were fabricated on two different sides of the optical fiber substrate. The UV sensing test was achieved by monitoring the optoelectrical characteristics of the single IGZO-based FET, enabling switching of the component. Note that the UV detection was carried out by measuring the change of drain current in the FET device. UV-LED light (470-nm) and UV-laser light (404-nm) irradiated toward both the top and bottom of the chip on a fiber, implying UV sensing “out of fiber” and “through fiber core”, are shown in Figs. 3A and 3D, respectively. Figure 3B presents the transfer characteristics of the FET on the outer surface of the fiber before and after UV exposure ($V_D = 5$ V). As a UV sensing component, the IGZO-based FET responded to exposed UV light, and the off-current increased. This implies that exposed light contributes to the generation of charge carriers in the IGZO channel. It should be noted that the irradiated UV light out of fiber is partially blocked or scattered by the gate metal electrode due to the TG/BC structure of the FET device. Although the photo-to-dark current ratio is relatively low, it provides enough electrical signal to enable the device to detect UV illumination at unknown environmental conditions (Fig. 3C). Meanwhile, we also found one more possible application as a signal transducer of the IGZO-based FET on the fiber. Figure 3D illustrates the schematics of the signal transducer. The UV laser is irradiated through the fiber core and is propagated within the single FET fabricated on the optical glass fiber. The off-state current in the I_D - V_G curves remarkably increases by about three orders of magnitude when the IGZO semiconductor is excited by light propagation inside the optical fiber (Fig. 3E). The temporal response between the drain current and time (I_D -time) with various laser intensities showed a stable switching and relatively high photo-to-dark current ratio, while V_D and V_G were maintained at 5 V and -5 V, respectively (Fig. 3F). It will be possible to realize a high-performance photosensor or signal transducer by using photosensitive semiconducting materials and different device architectures, such as bottom-gate/top-contact device architecture and perpendicular type diodes. In this regard, the IC on optical fiber can be utilized not only as a photodetector but also to construct the wireless sensor networks that are powered by laser beam propagation²³.

Lastly, to allow multifunctionality of the chip on a fiber, resistive-type sensors are directly integrated on the other side of the fiber, as shown in Fig. 4. For efficient measurement and detection of thermal information, Ni and Cr were selected as the thermoresistive materials because these pure metals can be easily deposited by vacuum thermal evaporation and have high Seebeck coefficients ($-19 \mu\text{V K}^{-1}$ for Ni

and $+20 \mu\text{V K}^{-1}$ for Cr), which can generate large thermoelectric voltages and signals for temperature monitoring (see Supplementary information).²⁴ The interval distance between each thermocouple is 3.4 mm and the contact pads of three thermocouples are located on one side of the fiber surface. The temperature sensors on a fiber operate through voltage changes induced in response to the temperature at different positions along to the fiber. Those multiple integrations of sensors on fiber enable precise monitoring of temperature at environmental conditions. By setting up the circuit as shown in Fig. 4A and sharing the ground contact, the temperature can be measured at three points simultaneously. Furthermore, the change in thermoelectric voltages (ΔV_{TE}) with increasing temperature of thermal source (T_{Source}) and with the temperature difference between thermally synchronized thermocouples is measured at a given temperature and room temperature, respectively ($T_{\text{TC}} - T_{\text{RT}}$). The detailed discussion about each sensor is described in Supplementary Fig. S5.

Due to the unique shape of our chip on a fiber, it can be applied as an implantable temperature sensing module as shown in Fig. 4B. To monitor the temperature of the heat source, the integrated sensing fiber tip is carefully implanted to a hot block. As a result of thermal conduction from the thermal source to the sensor through the body of the fiber, the temperature in a material was successfully monitored spontaneously by changing the temperature of the heat source. The thermoelectric voltages (ΔV_{TE}) of each thermocouple on the fiber were linearly responded by changing the temperature of the heat block from room temperature to 60 °C, exhibiting lower values in order away from the thermal source ($T_{\text{Source}} > T_{\text{TC-1}} > T_{\text{TC-2}} > T_{\text{TC-3}}$) (Fig. 4C). Although the detected temperature decreased exponentially as the position of the temperature sensor moved away from the heat source due to heat loss from air convection, as shown in Fig. 4D, the calculated temperature at each integrated sensor on the fiber exhibited clear stepwise behavior. This implies that the integrated 1D thermoresistive sensors are applicable to not only wearable temperature sensing network systems but also implantable modules. Hence, the above results, together with the UV/thermal sensing and electronic components on a fiber, can offer substantial promise for implementation of high performance and multifunctional electronic fiber systems for future wearable electronic textile applications.

In summary, we demonstrated an innovative electronic fiber platform with integrated electronic devices on a one-dimensional monofilament fiber. For high integration density, the capillary-assisted coating method and maskless photolithography were implemented to quickly and directly draw the desired device design in high resolution at ambient conditions. The optimized process presents one way to fabricate miniaturized functional devices onto non-planar substrates. The chip on a fiber was composed of basic electronic units such as transistors, inverters, ring oscillators for data processing, as well as sensing or transducing units for detecting optical/thermal signals. The proposed device platform and process provide a new architecting type of fibrous devices and contribute to the realization of high-density electronic fiber embedded in clothes. We envision that this chip on a fiber platform will enable new technological advances in wearable electronic textiles as well as conventional batch-process based two-dimensional wafer electronics by adapting a reel-to-reel continuous fabrication process.

Methods

Material preparation

All materials used in this study were purchased as follows without any purification. Square shape monofilament (FP150QMT, Thorlabs), gold (Au, 99.99%, TAEWON SCIENTIFIC), chromium (Cr, CR-090010, 99.9%, Nilaco), nickel (Ni, NI-311165, 99.9%, Nilaco), IGZO sputtering target ($\text{In}_2\text{O}_3 : \text{Ga}_2\text{O}_3 : \text{ZnO} = 1 : 1 : 1$ in atom%, 99.99%, Advanced Engineering Materials), Au etchant (Gold Etchant, Sigma Aldrich), Cr etchant (CR-7, KMG Electronic Chemicals), Ni etchant (Nickel Etchants, TRANSENE), Al_2O_3 etchant (Aluminium Etch ANPE 80/5/5/10 Microchem), IGZO etchant (HCl, 35%, Wako), Positive photoresist (AZ GXR 601, AZ Electronic Materials), Developer (AZ 300 MIF Developer, Merck)

Device fabrication

The square-shaped monofilaments ($150\text{ }\mu\text{m} \times 150\text{ }\mu\text{m} \times 7.5\text{ cm}$) were ultrasonically cleaned in deionized water, acetone, and isopropanol for 5 min. This was followed by ultraviolet-ozone (UV/ O_3) treatment for 15 min. Metal electrodes were patterned through maskless photolithography. A 2- μm -thick photoresist layer was coated on the fiber substrate using a capillary tube-assisted coating (CTAC) process (speed 1.0 mm min^{-1}), baked on a hot plate at $100\text{ }^\circ\text{C}$ for 2 min, and exposed to ultraviolet light using a maskless aligner (MLA 100, HEIDELBERG) with an energy density of about 200 mJ cm^{-2} and $1000\text{ }\mu\text{m sec}^{-1}$ of driving speed. The sample was immersed in developer for 2 min and rinsed with deionized water after hard baking ($100\text{ }^\circ\text{C}$ for 2 min). A 10-nm-thick Cr adhesion layer, followed by a 30-nm-thick Au, were deposited and patterned by soaking the fiber substrate in a bath of resist remover. Notably, 50-nm-thick Cr and 50-nm-thick Ni layers were deposited by vacuum evaporation at a base pressure of ca. $\sim 10^{-6}$ torr and speed $0.5\text{ }\text{\AA sec}^{-1}$ for thermocouples. IGZO thin films (15 nm) were deposited using an AC sputter (ACT ORION 8 Sputtering System, AJA International, 100 W, $\text{Ar} : \text{O}_2 = 20.0 : 0.2\text{ sccm}$, 2×10^{-3} torr). After deposition, the as-deposited IGZO films were placed on a hot plate and thermally annealed for 30 min at $300\text{ }^\circ\text{C}$ in ambient air to improve the quality of the IGZO film. Al_2O_3 (thickness of 36.1 nm) for the gate dielectric and encapsulation layers was directly deposited by the atomic layer deposition system (LUCIDA D100 ALD, NCD). Trimethylaluminum and deionized water were used as the precursors and oxidants in this system, respectively. The substrate temperature was maintained at $100\text{ }^\circ\text{C}$ during the 400 cycles of the deposition process. In the wet-etching sequence, each etchant for each material was purchased commercially and used after being diluted by deionized water. The detailed conditions are as follows. Au etchant: 1/20 for 3 min; Cr etchant: 1/20 for 3 min; Ni etchant: 1/20 for 3 min; IGZO etchant: 1/100 for 2 min; Al_2O_3 etchant: $50\text{ }^\circ\text{C}$ for 4 min. After each wet-etching processes was completed, the samples were washed with deionized water, transferred to the acetone bath at $100\text{ }^\circ\text{C}$, and immersed for 5 min to remove the photoresist.

Device and film characterization

Current-voltage characteristics were measured with a HP4145B (HP Ltd.), Keithley 4200SCS (Keithley Instruments, Ltd.), and a digital phosphor oscilloscope DPO2002B (Tektronix, Ltd.) in ambient air. The optoelectrical and electrical characteristics of the phototransistor were measured using a Keithley 4200 semiconductor characterization system under illumination of wavelength for 470 nm (UV-LED light of 50mW/cm²). To measure the optoelectrical signal of UV light traveling through the fiber, 404 nm of UV-laser light (50mW) was employed. SEM and optical microscope images were obtained using a Nova NanoSEM 450 (FEI Ltd.) and Nikon ECLIPSE LV150 microscope (Nikon), respectively. The thickness of thin films was determined from a surface profiler (ET200, Kosaka Laboratory Ltd.). X-ray photoelectron spectroscopy (XPS) measurements were performed using an ESCALAB250Xi (Thermo Fisher Scientific, USA) at a basic pressure of 10⁻⁹ mbar.

Declarations

Corresponding Author

E-mail: twk@jbnu.ac.kr

Author Contributions

T.W.K. developed the idea. S.H., A.L., conducted the experiments, and S.H., M.K., A.L., S.B., S.K. L., S.H.L., T.L., G.W., T.W.K. collected and analyzed the data. S.H., M.K., T.W.K. wrote the manuscript. All authors discussed the results and commented on the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (2020R1A2C2010163). T.L. thanks the financial support of the National Creative Research Laboratory program (Grant No. 2012026372).

References

1. Rein, M., Favrod, V.D., Hou, C., Khudiyev, T., Stolyarov, A., Cox, J., Chung, C.C., Chhav, C., Ellis, M., Joannopoulos, J. & Fink, Y. Diode fibres for fabric-based optical communications. *Nature* **560**, 214–218 (2018).
2. Chen, G., Li, Y., Bick, M. & Chen, J. Smart textiles for electricity generation. *Chem. Rev.* **120**, 3668–3720 (2020).
3. Loke, G., Alain, J., Yan, W., Khudiyev, T., Noel, G., Yuan, R., Missakian, A. & Fink, Y. Computing fabrics. *Matter* **2**, 786–788 (2020).

4. Yu, L., Parker, S., Xuan, H., Zhang, Y., Jiang, S., Tousi, M., Manteghi, M., Wang, A. & Jia, X. Flexible multi-material fibers for distributed pressure and temperature sensing. *Adv. Funct. Mater.* **30**, 1908915 (2020).
5. Weng, W., Yang, J., Zhang, Y., Li, Y., Yang, S., Zhu, L. & Zhu, M. A route toward smart system integration: from fiber design to device construction. *Adv. Mater.* **32**, 1902301 (2020).
6. Wang, L., Fu, X., He, J., Shi, X., Chen, T., Chen, P., Wang, B. & Peng, H. Application challenges in fiber and textile electronics. *Adv. Mater.* **32**, 1901971 (2020).
7. Yetisen, A. K., Martinez-Hurtado, J. L., Ünal, B., Khademhosseini, A. & Butt, H. Wearables in Medicine. *Adv. Mater.* **30**, 1706910 (2018).
8. Kwon, S., Kim, H., Choi, S., Jeong, E. G., Kim, D., Lee, S., Lee, H. S., Seo, Y. C., & Choi, K. C. Weavable and highly efficient organic light-emitting fibers for wearable electronics: a scalable, low-temperature process. *Nano Lett.* **18**, 347–356 (2018).
9. Yang, T., Xie, D., Li, Z. & Zhu, H. Recent advances in wearable tactile sensors: materials, sensing mechanisms, and device performance. *Mater. Sci. Eng., R.* **115**, 1–37 (2017).
10. Liao, X., Liao, Q., Zhang, Z., Yan, X., Liang, Q., Wang, Q., Li, M. & Zhang, Y. A highly stretchable ZnO@fiber-based multifunctional nanosensor for strain/temperature/UV detection. *Adv. Funct. Mater.* **26**, 3074–3081 (2016).
11. Zhong, J., Zhang, Y., Zhong, Q., Hu, Q., Hu, B., Wang, Z. L. & Zhou, J. Fiber-based generator for wearable electronics and mobile medication. *ACS Nano* **8**, 6273–6280 (2014).
12. Heo, J. S., Eom, J., Kim, Y. -H. & Park, S. K. Recent progress of textile-based wearable electronics: a comprehensive review of materials, devices, and applications. *Small* **14**, 1703034 (2018).
13. Liu, L. X., Chen, W., Zhang, H. B., Wang, Q. W., Guan, F. & Yu, Z. Z. Flexible and multifunctional silk textiles with biomimetic leaf-like MXene/Silver nanowire nanostructures for electromagnetic interference shielding, humidity monitoring, and self-derived hydrophobicity. *Adv. Funct. Mater.* **29**, 1905197 (2019).
14. Ham, S., Kang, M., Jang, S., Jang, J., Choi, S., Kim, T. W. & Wang, G. One-dimensional organic artificial multi-synapses enabling electronic textile neural network for wearable neuromorphic applications. *Sci. Adv.* **6**, eaba1178 (2020).
15. Yan, W., Page, A., Nguyen-Dang, T., Qu, Y., Sordo, F., Wei, L. & Sorin, F. Advanced multimaterial electronic and optoelectronic fibers and textiles. *Adv. Mater.* **31**, 1802348 (2019).
16. Karnaushenko, D., Kang, T., Bandari, V. K., Zhu, F. & Schmidt, O. G. 3D self-assembled microelectronic devices: concepts, materials, applications. *Adv. Mater.* **32**, 1902994 (2020).
17. Kang, M., Lee, S. A., Jang, S., Hwang, S., Lee, S. K., Bae, S., Hong, J. M., Lee, S. H., Jeong, K. U., Lim, J. A. & Kim, T. W. Low-voltage organic transistor memory fiber with a nanograined organic ferroelectric film. *ACS Appl. Mater. Interfaces* **11**, 22575–22582 (2019).
18. McKenna, C., Walsh, K., Crain, M. & Lake, J. Maskless direct write grayscale lithography for MEMS applications. *Proc. 18th Biennial Univ./Government/Ind. Micro/Nano Symp.*, 1–4 (2010).

19. Yoon, J., Jeong, Y., Kim, H., Yoo, S., Jung, H. S., Kim, Y., Hwang, Y., Hyun, Y., Hong, W. K., Lee, B. H. & Choa, S.H. Robust and stretchable indium gallium zinc oxide-based electronic textiles formed by cilia-assisted transfer printing. *Nat. Commun.* **7**, 1–10 (2016).
20. Cai, W., Zhang, J., Wilson, J. & Song, A. Low-voltage, full-swing InGaZnO-based inverters enabled by solution-processed, ultra-thin Al_xO_y. *IEEE Electron Device Lett.* **40**, 1285–1288 (2019).
21. Ok, K., Oh, S., Jeong, H., Bae, J. U. & Park, J. Effect of alumina buffers on the stability of top-gate amorphous InGaZnO thin-film transistors on flexible substrates. *IEEE Electron Device Lett.* **36**, 917–919 (2015).
22. Hwang, B. U., Kim, D. I., Cho, S. W., Yun, M. G., Kim, H. J., Kim, Y. J., Cho, H. K. & Lee, N. E. Role of ultrathin Al₂O₃ layer in organic/inorganic hybrid gate dielectrics for flexibility improvement of InGaZnO thin film transistors. *Org. Elect.* **15**, 1458–1464 (2014).
23. Jin, Z., Ye, F., Zhang, X., Jia, S., Dong, L., Lei, S., Vajtai, R., Robinson, J. T., Lou, J. & Ajayan, P. M. Near-field coupled integrable two-dimensional InSe photosensor on optical fiber, *ACS Nano* **12**, 12571–12577 (2018).
24. Hwang, S., Potscavage, W.J., Yang, Y.S., Park, I.S., Matsushima, T. & Adachi, C. Solution-processed organic thermoelectric materials exhibiting doping-concentration-dependent polarity. *Phys. Chem. Chem. Phys.* **18**, 29199–29207(2016).

Figures

Figure 1

Chip on a fiber system. A, Schematic illustrations of e-textile integrated from a multifunctional electronic fiber and wearable application. B, Cross-sectional, and three-dimensional scheme of the device elements fabricated on the microfiber substrate. C, SEM image of electronic devices fabricated on a single fiber. D, Photograph of the flexible electronic fiber.

Figure 2

Electrical characteristics of integrated electronic components on a fiber. A, A photograph and the circuit diagrams of an inverter based on IGZO-based FETs fabricated on a flexible fiber substrate. B, I_D - V_G curves of an IGZO FET representative of the fiber device. The FET has a channel length (L) of 10 μm and a channel width (W) of 50 μm . C, Static transfer properties of the inverter based on two IGZO FETs for a supply voltage (V_{DD}) of 2 V ~ 5 V and bias voltage (V_{bias}) of 5 V. D, A photograph and the circuit diagram of a five-stage ring oscillator based on the depletion-load inverters fabricated on the microfiber. E, Dynamic characteristics of the ring oscillator in response to different supply voltages (V_{DD}). F, Current amplitude (A), frequency, and propagation delay measured for a V_{DD} of 2, 3, 4, and 5 V. G, Schematic

illustrations of the integrated fiber device on a PET substrate (left) and I_D - V_G characteristics of the IGZO FETs (right) under bending conditions. Mechanical strain (ϵ) is calculated using the bending radius (R). The insets show photographs of the flexible fiber device measured during the bending. H, Change of on-current states, field-effect mobilities, and threshold voltages as a function of mechanical strain with forward and backward bending.

Figure 3

Optoelectrical characteristics of phototransistors on a fiber. A, Schematics and a photograph of the optoelectrical measurement when the outside of the fiber device is irradiated by UV light. B, Transfer curves of the IGZO-based phototransistor in the dark and under the exposure of UV light. C, Time-dependent photoresponse at different gate voltages under the pulsed illumination of UV light. D, Schematics of the optoelectrical measurement when the inside of the fiber device is irradiated by 404-nm laser light. E, Transfer characteristics of the phototransistor in the dark and during the exposure of UV light in the fiber core. F, Transient photocurrent of the IGZO device with different laser powers of 4.2 V, 4.6 V, and 5.0 V.

Figure 4

Thermoelectrical characteristics of thermal sensing components integrated on a fiber. A, Photograph and schematic diagram of the thermosensing components. B, Schematic illustration of the integrated thermocouples on a fiber and temperature gradient across the fiber device. C, Changes of thermoelectric voltages of each thermocouple as a function of temperature. D, Temperature distribution as a function of distance from the heat source to each sensor.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SIforNatureNanotechnologyCOF20200930.docx](#)