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2018

Liao, X., Song, W., Zhang, X., Huang, H., Wang, Y., & Zheng, Y. (2018). Directly printed wearable electronic sensing textiles towards human – machine interfaces. *Journal of Materials Chemistry C*, 6(47), 12841-12848. doi:10.1039/c8tc02655f

<https://hdl.handle.net/10356/137133>

<https://doi.org/10.1039/c8tc02655f>

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Directly Printed Wearable Electronic Sensing Textiles towards Human-Machine Interfaces

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Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

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Gesture control is an emerging technological goal in the field of human-machine interfaces (HMIs). Optical fibers or metal strain sensors as sensing elements are generally complex and not sensitive enough to accurately capture gestures, which need to additional complicated signal optimization. Electronic sensing textiles hold great promise for the next generation of wearable electronics. Here, soft, deformable and ultrahigh-performance textile strain sensors are fabricated by directly stencil printing silver ink on pre-stretched textiles towards HMIs. The textile strain sensors possess ultrahigh sensitivity (a gauge factor of ~2,000), stretchability (up to 60% strain), and durability (>10,000 stretching cycles). Through a simple auxiliary signal processing circuit with Bluetooth communication technology, an intelligent glove assembled with the textile strain sensors is prepared, which is capable of detecting full range of fingers' bending and can translate the fingers' bending into wireless control commands. Immediate applications, involving smart car director, wireless typing, and remote PowerPoint controller, bring out the great practical value of the textile strain sensors in the field of wearable electronics. This work provides a new prospective for achieving wearable sensing electronic textiles with ultrahigh performance towards HMIs, and will further expand the impact in the field of Internet of Things.

Introduction

Wearable electronics, due to the fascinating efficacy, are attractive candidates in the field of human-machine interfaces (HMIs).¹⁻⁴ Compared with conventional electronic devices, wearable electronics are based on flexible or stretchable materials, and achieve significant progress along with the development of materials or preparation techniques.⁵⁻⁷ Flexible pressure or strain sensors are essential components of wearable electronics, and provide easy and intuitive interactive channels between human and external machines.^{8,9} Through utilizing piezoelectric,¹⁰⁻¹³ triboelectric,¹⁴⁻¹⁸ optical,¹⁹⁻²¹ capacitive,²²⁻²⁵ or resistive²⁶⁻³³ transduction mechanisms, various flexible pressure or strain sensors have been realized. Resistive strain-sensing devices are based on resistance change in response to external strain. Relying on simplicity in reading method and relative convenience in post-circuit processing, the resistive strain-sensing devices grip constantly increasing attention of exploitation and utilization.^{26,27,34-36}

Electronic textiles (e-textiles) hold great promise for the next generation of wearable electronics.³⁶⁻⁴¹ Sewing, weaving, non-woven, knitting, and breeding are general methods used for fabricating textiles.⁴²⁻⁴⁴ As the characteristics of filaments, yarn, or/and fabrics used, e-textiles feature soft, deformable and comfortable, and are directly worn on the human body.^{42,45,46} Some endeavours have been devoted to facilitating e-textiles to become interactive devices or detect human activities.^{14,39,47-50} Feasible and novel strategies to prepare resistive textile strain sensors, the key elements of e-textiles, include the hybrid structures of carbon fibre–zinc oxide (ZnO) nanowire,⁴⁷ full aqueous solution preparation of ZnO nanowires over polyurethane (PU) fibres,³⁹ and carbonizing cotton fabrics.⁴⁸ Despite this progress, the performance, especially the sensitivity, of most resistive textile strain sensors is not so desirable. It is still an enormous challenge to achieve high sensitivity. Furthermore, a low-cost and easy-to-fabricate way is a strong demand to construct resistive textile strain sensors. Besides, integrated multiple textile strain sensors by far are seldom reported for wearable wireless control of HMIs.

Herein, we propose an ultrasensitive strain sensor by stencil printing silver ink on a pre-stretched textile. The method presented here characterizes facility and scalability, and may inspire manufacturing strategy of other stretchable electronics. The textile, as a stretchable substrate, is composed of elastic latex threads as core fibre and polyester filaments as outer wrapping fibre, and offers stretchability to curve human fingers well. Due to the pre-stretching action, the silver microflakes not only cover the textile well but also fill inside the micro gaps among the polyester filaments. It makes the initial resistance of the device small, and will keep the conductive paths connected

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^{*}Electronic Supplementary Information (ESI) available. See DOI: 10.1039/x0xx00000x

when the device is stretched. The effects contribute to the high sensitivity of the as-prepared textile strain sensor for detecting relatively large strain. Noteworthy, the textile strain sensor also has other significant inherent advantages, including fast response time, remarkable response stability, simplicity in reading method, and convenience in post-circuit processing. Through Bluetooth communication technology, a wearable intelligent glove assembled with multiple textile strain sensors is fabricated for translating fingers' bending into the wireless control commands of a smart toy car, typing, and PowerPoint display to demonstrate the broad application prospects. Importantly, attributing to the high performance of the textile strain sensors, this analog-to-digital conversion circuit does not need any complicated additional signal optimization such as signal amplification, noise reduction, or baseline tracking. Based on the satisfactory sensing properties and stretchability, we believe that the textile strain sensor presented here would achieve various development for future HMI application, and may further expand the impact in the field of Internet of Things (IoT).

Experimental section

Materials and devices fabrication

A stretchable textile (thickness of ~ 1.1 mm, Jinhua Feifei Garment Sewing Shop, in Zhejiang Province, China) composed of elastic latex threads as core fibre and polyester filaments as outer wrapping fibre, was cleaned with ethyl alcohol, and then was dried by a hot plate (WH220 PLUS, WIGGENS). The pre-processed textile band was fixed at 40% strain state by using two pins. As silver ink was moved forward during the stencil printing process by using a squeegee (Fig. S1a in the ESI[†]), it would escape from the interspaces between the clusters of polyester filaments when the pre-stretched strain of the textile band was over 40%. The stencil was patterned with adhesive tape (Scotch^{TM} Magic Tape 810, 3M Inc.). Then, a Teflon slide conducted as a squeegee was utilized to print silver ink (Shenzhen Tiangong Maintenance Tool Shop, in Guangdong Province, China) on the pre-stretched textile band (Fig. S1a in the ESI[†]). After pre-drying for 10 minutes, the textile band printed with silver ink was subjected to 80% stretching strain (Fig. S1b in the ESI[†]). Multiple stretching-releasing cycles were repeated on the textile band (Fig. S1c in the ESI[†]). Finally, the textile band printed with silver ink was dried at room temperature (Fig. S1d in the ESI[†]). For the assembly of wearable intelligent glove, the length and width of the textile strain sensors were 40 mm and 8 mm, respectively.

Properties measurements and characterization

The morphology of the textile strain sensors was characterized by using scanning electron microscopy (JEOL-JSM 6360). The element distribution was analysed by energy dispersive X-ray detector (JEOL-JED 2300). Semiconductor characterization system (Keithley 4200A-SCS), a high precision digital multimeter (Agilent 34461A), and a standard digital multimeter (UNIT

UT39B) combined with a designed actuator (Beijing Times Brilliant Electric Technology Co., Ltd.) were used to test electromechanical properties and resistive responses of the textile strain sensors.

Results and discussion

Scheme for stencil printing and assembling textile strain sensor towards HMIs is illustrated in Fig. 1a. In general, stencil printing is used to deposit functional material on non-stretchable substrate.³⁴ However, the type of devices is subjected to limited sensing range, which may restrict them in more applications in the future. Stencil printing presented here was utilized to directly deposit silver ink on a pre-stretched textile. Through the facile stencil printing with a Teflon slide acted as a squeegee and patterned 3M tape regarded as stencil, commercial silver ink was directly printed on and soaked inside a pre-stretched textile, which was made of polyester filaments and elastic latex threads. Notably, unlike many common fabrication methods of stretchable devices, such as photolithography, chemical vapor deposition and hydrothermal method, the stencil printing method presented here was relatively simple and effective and did not need long-time, hyperthermal, vacuum, or other complicated producing processes. It would have important guiding significance for future industrial applications. The pre-stretching action effectively made the silver ink not only cover the textile well but also fill inside the micro gaps among the polyester filaments. The as-prepared textile strain sensor could highly sensitively detect relatively large strain sensing range without any electric signal interrupts. More details of the stencil printing process for preparing the textile strain sensor are presented in the Experimental Section and Fig. S1 in the ESI[†].

The scanning electron microscope (SEM) was employed to observe the morphology of the silver microflakes film, which was printed on the textile. These silver microflakes were overlapped and tightened with each other, which brought about good electrical conductivity of the textile printed with silver ink (Fig. 1b). The boundary line between printed and non-printed textile is obvious in Fig. 1c, where the silver microflakes' spreading and permeating the clusters of polyester filaments is also clearly observed. The obvious difference between the printed textile and naked textile was further confirmed by using energy dispersive X-ray spectrometer (EDS) (Fig. 1d and Fig. S2 in the ESI[†]). The surface distribution of the silver element was clearly observed from the green patterned image (Fig. 1d), which was the mapping image of the silver element from Fig. 1c. This result manifested that the pristine textile did not have the presence of conductive elements, and only be conductive after being printed with silver ink. In addition, this conductive textile was capable of further serving as a textile strain sensor, which would be confirmed in the following. The cross-sectional SEM image of the textile printed with silver ink (Fig. S3 in the ESI[†]) further revealed that the silver microflakes not only covered the textile well but also filled inside the micro gaps among the polyester filaments. The silver ink easily penetrated to the micro gaps among the polyester filaments, showing the significant effect of the pre-stretching action. Fig. 1e is an EDS spectrum of

Fig. 1 Construction and characterization of textile strain sensor. (a) Scheme for stencil printing the textile strain sensor. (b) Scanning electron microscope (SEM) image of the printed silver microflakes film. (c) SEM image of the partial textile stencil printed with silver ink. (d) Surface distribution image of the silver element mapped from (c). The green patterned image was the distribution of the silver element. (e) Energy dispersive X-ray spectrometer (EDS) spectrum of the textile strain sensor. (f) Photographs of the textile strain sensor stretched from 0% to 60% strain, and then released to 0% strain.

the textile printed with silver ink, which indexes the characteristic diffraction peaks of silver element. It fully indicated that the silver microflakes were the main conductive materials of the textile printed with silver ink. In addition, it should be noted that the textile printed with silver ink belonged to the resistive strain-sensing devices, due to its ohmic behaviour no matter strain was applied or not (Fig. S4 in the ESI†). Thus, the textile printed with silver ink could be exploited as a textile strain sensor. Owing to the stretchability of the elastic latex threads and the wrapped microstructures of the polyester filaments, the textile strain sensor could be stretched up to 60% strain, and was released to original state without any evident of tensile failure or plastic deformation (Fig. 1f). The results confirmed that the textile strain sensor was capable of detecting full range of fingers' bending. Hereinafter, multiple textile strain sensors were exploited to track gestures by assembling them into a wearable intelligent glove.

To investigate the deformation and fracturing mechanism, Fig. 2 provides critical information of the textile strain sensor at 0% and 40% strain states along with the direction of the core line of elastic latex threads. The typical SEM image of the surface morphology of the textile strain sensor is presented in Fig. 2a. At the initial stretching stage, the clusters of polyester filaments arranged neatly, and contacted closely with the adjacent clusters, which would make the initial resistance of the device small and thus contributed to the relatively high sensitivity of the as-prepared strain sensor. Fig. 2b shows the SEM image of the stretched textile strain sensor supplied by 40%

strain. At this stage, the clusters of polyester filaments accommodated the deformation by producing interspaces and tilting the direction towards the stretching axis. Importantly, the clusters of polyester filaments were separated at micro scale from each other along with the same core line of elastic latex threads, while they kept the integrity of the wrapped microstructures and were bridged by the adjacent clusters on the parallel core line. To confirm the distribution states of the silver microflakes, Figs. 2c and 2d show the surface distribution images of the silver element of the textile strain sensor stretched by 0% and 40% strain, respectively. There was no significant change of the distributions of the silver microflakes on the clusters of polyester filaments. Notably, the silver microflakes were spread over the cluster of polyester filaments, and did not come into being any significant peeling or fading when stretched, except that their patterned shapes varied with the clusters. In fact, the conductive channels of the textile strain sensor relied on the clusters of polyester filaments, where the silver microflakes were spread. Therefore, in the following parts, they were called as conductive modules. Then, the textile strain sensor could be thought as the composite that consisted of conductive modules arrays. As mentioned above, the contact between the conductive modules always existed, reflecting always existing transmission channels of electrons. It also revealed that the textile strain sensor kept working even when the device was stretched. Figs. 2e and 2f are the energy intensity of the silver element in the yellow wireframe area in Figs. 2c and 2d, respectively. The sharp peaks seen from the

Fig. 2 Deformation and fracturing mechanism of textile strain sensor. (a, b) SEM images of the textile strain sensor at 0% and 40% strain states. (c, d) Surface distribution image of the silver element of the textile strain sensor stretched by 0% and 40% strain, respectively. Notably, (c) and (d) corresponded to (a) and (b), respectively. The green patterned image was the distribution of the silver element. (e, f) Energy intensity of the silver element in the yellow wireframe area of (c) and (d), respectively.

figures reflected the number of the conductive modules. Within the same range scale, it was found that not only the number of conductive modules was changed at the stretched state of the textile strain sensor, but also the conductive modules generated slight expansion. The results indicated that the stretching strain did not make the conductive paths of the textile strain sensor interrupt in spite of changing the conductive paths, which was contributed to the fact that the silver microflakes not only covered the textile well but also filled inside the micro gaps among the polyester filaments. Due to this distinctive shape and deformation of the conductive modules, the transmission channels of electrons would be changed between the conductive modules when external strain was applied on them. Accordingly, the resistance of the textile strain sensor would be increased.

Fig. 3a illustrates the simplified schematic diagram of sensing mechanism of the textile strain sensor, which is based on percolation theory. In the diagram, hexagonal structures are representative of conductive modules. C_1 and C_1' are alternate representations, respectively, of boundary transmission channels of electrons between the conductive modules at original state and stretched state of the textile strain sensor. Relatively, transmission channels at the contact corner among the adjoining conductive modules are expressed as C_2 and C_2' , respectively. At the original state, no external strain is applied on the textile strain sensor, and electrons pass through the conductive modules smoothly through C_1 and C_2 channels. After stretching, the conductive paths of the textile strain sensor are still connected through generating microcracks instead of

interrupting, which is confirmed in Fig. 2. At this state, interspaces are generated between the conductive modules, and make electrons difficult to pass through the conductive modules. In addition, slight expansion of the conductive modules and change of their direction, as mentioned above, both extend the transmission channels (C_1' and C_2') of electrons. Therefore, these two situations work together to influence the movement of electrons, leading to the increase in resistance of the textile strain sensor. As demonstrated, the sensing mechanism is directed to the strain-resistive response that transmission channels of electrons are principally affected by the change of conductive modules, eventually resulting in the change of resistance.

Fig. 3b shows that the change of the normalized resistance is noticeable and nearly linear to the stretching strain, which is up to 60%. In general, sensitivity is defined as the value of the normalized resistance $((R - R_0)/R_0)$, R and R_0 are the resistance of the sensor at stretched and original states, respectively) versus external strain (ϵ). Here, the calculation of the sensitivity of the textile strain sensor is characterized by the formula $GF = \Delta R/R_0/\epsilon = (R - R_0)/R_0/\epsilon$, where GF is the gauge factor. The experimental result revealed that the GF of the textile strain sensor was estimated as $\sim 2,000$. Compared to the performance of other textile or fibre-based strain sensors reported recently (Table S1 in the ESI[†]), the textile strain sensor presented here possessed ultrahigh sensitivity with a relatively wide sensing range. Previous studies have demonstrated that the

Fig. 3 Sensing mechanism and properties of textile strain sensor. (a) Schematic diagram of sensing mechanism of the textile strain sensor. Notably, the hexagonal structures were representative of conductive modules. (b) Normalized resistance of the textile strain sensor under different strain. (c) Response time and decay time measurement of the textile strain sensor. (d) Various relative resistance response of the textile strain sensor under the 5%, 10%, 25%, and 50% strain. (e) Multicycle tests of the resistance change of the textile strain sensor under 10% stretching strain at the frequency of 1 Hz. (f) Durability test of the textile strain sensor by applying 10% stretching strain at the frequency of 1 Hz. The variation curves of resistance were presented after each 2,000 cycles of strain loading-unloading.

microcracks would make the strain sensor more sensitive than that of devices without microcracks.^{27,33-35} Besides, it was an effective strategy to further increase the sensitivity by decreasing the initial resistance of the devices according to the definition of GF. Based on these two aspects, ultrahigh sensitivity of the textile strain sensor was achieved. Fig. S5 in the ESI† provides that the counterpart prepared without any pre-stretching action characterizes a very limited sensing range (maximum 5% strain), and will be insulated upon further stretching. Due to the pre-stretching action, the silver microflakes not only covered the textile well but also filled inside the micro gaps among the polyester filaments. It made the initial resistance of the device small and further kept the conductive paths of the textile strain sensor connected through

generating microcracks when the device was stretched. The effects contributed to the high sensitivity of the as-prepared textile strain sensor for detecting strain in the relatively large range. Unlike many common fabricating methods of stretchable devices, the method presented here characterized facility and low cost, and may inspire manufacturing strategy of other stretchable electronics. We vision that higher sensitivity and larger detection range would be achieved by pre-stretching optimization combined with other preparation processes.

Next, the tests of response time and decay time of the textile strain sensor were carried out. Fig. 3c indicates that the textile strain sensor features fast response time of ~10 ms and decay time of ~15 ms. Such response time would be outstanding enough for normal operations in daily lives. In the following

experiments, the electromechanical stability of the textile strain sensor was evaluated to probe the response and recovery properties under static stretching strain. Several tests were performed by using relatively large stretching strain of 5%, 10%, 25%, and 50% (Fig. 3d). The result showed that the response of the textile strain sensor was stable and varied to different stretching strain, regardless of small overshoots generated by the slow creep of the textile substrate. Furthermore, durability of the textile strain sensor was examined by applying 10% strain with frequency of 1 Hz. Fig. 3e shows that the resistance response of the textile strain sensor is repeatable, and the response wave shape is almost the same as the initial shape. Further response tests were lasted for > 10,000 loading-unloading strain cycles (Fig. 3f). The performance reduced only 10.2%, presenting high durability, stability, and repeatability of the textile strain sensor.

Gestures play significant roles and are natural communication interfaces between people. Optical fibres or metal strain sensors as sensing elements are generally complex and not sensitive enough to accurately capture gestures, which need to additional complicated signal optimization. As a proof of concept, in Fig. 4, we demonstrated some practical capabilities of the textile strain sensors towards HMIs. Importantly, the analog-to-digital conversion circuit did not need any additional signal optimization such as signal amplification, noise reduction or baseline tracking, which was attributed to the high performance of the textile strain sensor. Fig. 4a illustrates the scheme diagram of an intelligent glove to wireless communication between human fingers and smart machines, involving smart car director, wireless typing, and remote PowerPoint controller. A micro controller board (MCU, Arduino Mega 2560, 16 Analog input ports) was utilized to convert analog signals from the textile strain sensors into digital signals. Subsequently, A Bluetooth transceiver module was used to send wireless commands (Fig. 4b). Through a simple signal processing circuit with the Bluetooth transceiver module, the intelligent glove assembled with five textile strain sensors was prepared. Each glove's finger joint was attached one textile strain sensor by using double-sided tape (VHB4910, 3M Inc.) (Fig. 4c). With verification, the intelligent glove could track the bending states (short bending and long bending) of human fingers with good stability, reflected by the changes of normalized resistance from the five textile strain sensors (Fig. 4d).

As illustrated in Fig. 4e, Fig. S6, Fig. S7, and Video S1 in the ESI†, the intelligent glove acted as a smart car director. The functional commands of "Turn on/off", "Go forward", "Go backward", "Turn left", and "Turn right" were respectively issued by thumb, index fingers, middle finger, ring finger, and little finger, respectively, to control the smart car (Fig. S7 in the ESI†). Furthermore, wireless typing was also realized by using the intelligent glove (Fig. 4f, Fig. S8, Fig. S9, and Video S2 in the ESI†). Fig. 4f presents a keyboard including 26 letters (from A to Z), a line feed exclamation character ("/"), and an exclamation mark ("!"). The small purple box highlighted the currently selected symbol (letter, character or mark). Once bending the thumb, the textbox would display the selected symbol. Other

functional commands of "Turn up", "Turn down", "Turn left", and "Turn right", to move in small purple box, were respectively controlled by the index finger, middle finger, ring finger, and little finger (Fig. S8 in the ESI†). Finally, the intelligent glove was applied to controlling PowerPoint slides (Fig. 4g, Fig. S10, Fig. S11, and Video S3 in the ESI†). Here, the short bending of thumb indicated the functional commands of "Turn on" and "Turn off". Long bending (>3 s) of thumb made the screen black. Other functional commands of "Page Up" and "Page down" were issued by the index finger and middle finger, respectively. The ring finger and little finger issued the functional commands of "Select hyperlink" and "Play video", respectively. For these applications, the textile strain sensors on each finger worked in sequence, which could not work simultaneously. Otherwise, the targeted subject was unable to accurately identify the control commands from the intelligent glove. As demonstrated in these applications, the textile strain sensors printed by a facile method exhibited their immediate capabilities for wearable electronics, and great potential for HMIs.

Conclusions

In summary, ultrasensitive textile strain sensors were fabricated through a facile and cost-effective stencil printing method. Based on the percolation theory, the sensing mechanism was directed to the strain-resistive response that transmission channels of electrons were principally affected by distinctive deformation of the percolatively conductive microstructures. The pre-stretching action was conducive to deposit silver ink well inside the textile, and further not only made the initial resistance of the device small but also kept the conductive paths of the textile strain sensor still connected through generating microcracks when the device was stretched. The as-fabricated textile strain sensor featured an ultrahigh GF of ~2,000 within the sensing range of 60% strain. Besides, the textile strain sensor also has other significant inherent advantages, including simplicity in reading method, convenience in post-circuit processing, fast response time of ~10 ms and remarkable response stability of >10,000 stretching-releasing strain cycles, to perform well in both static and dynamic operating conditions. As a proof-of-concept, an intelligent glove assembled with five textile strain sensors was prepared towards HMI applications, where it could be used to promptly translate fingers' bending into wireless control commands. Importantly, the analog-to-digital conversion circuit did not need any additional signal optimization such as signal amplification, noise reduction or baseline tracking, which was attributed to the high performance of the textile strain sensor. In this work, its practical applications were demonstrated as smart car director, wireless typing, and remote PowerPoint controller. Based on the satisfactory sensing properties and stretchability, we believe that the textile strain sensor presented here would achieve more various development for future HMI applications, and further expand the impact in the field of IoT.

Fig. 4 Applications of textile strain sensor. (a) Scheme diagram of wearable sensing electronic textiles to wireless communication between human fingers and smart machines. (b) Photographs of the microcontroller unit (MCU) for signal conditioning and the Bluetooth transceiver module for signal communication. (c) Photograph of the intelligent glove assembled with five textile strain sensors. (d) Normalized resistance responses of the five textile strain sensors, showing the bending states (short bending and long bending) of fingers. Demonstrations involving (e) smart car director, (f) wireless typing, and (g) remote PowerPoint controller were realized by using the intelligent glove.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The research was supported by the National Research Foundation of Singapore (No. NRF-CRP11-2012-01), the National Natural Science Foundation of China (61727808), and the National Key Research and Development Program of China (No. 2016YFB1001502).

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