Energy class project by Rohith Varikoti and Mohammad Avestan

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Tailorable and Wearable Textile Devices for Solar Energy Harvesting and Simultaneous Storage

An all-solid tailorable energy textile which is called tailorable textile device has been presented which is used for solar energy harvesting and storage simultaneously. The new technique allows us to design various shape and style by tailoring multifunctional textile without impeding its performance, which is used in producing of smart energy garment and provided wearable self-powering system. The fiber electrodes that form the threads can be produced in large scale and they could be woven to make energy textile. The energy storage module is a tailorable, ultrahigh bending resistance, with an ultra-charge capability is the fiber super capacitor, and the solar energy harvesting module is an all-solid dye-sensitized solar cell textile. This textile sample is able to be fully charged to 1.2 V during 17 second using self-harvesting solar energy, and at a discharge current density of 0.1 mA it could be discharged within 78 seconds.

Introduction

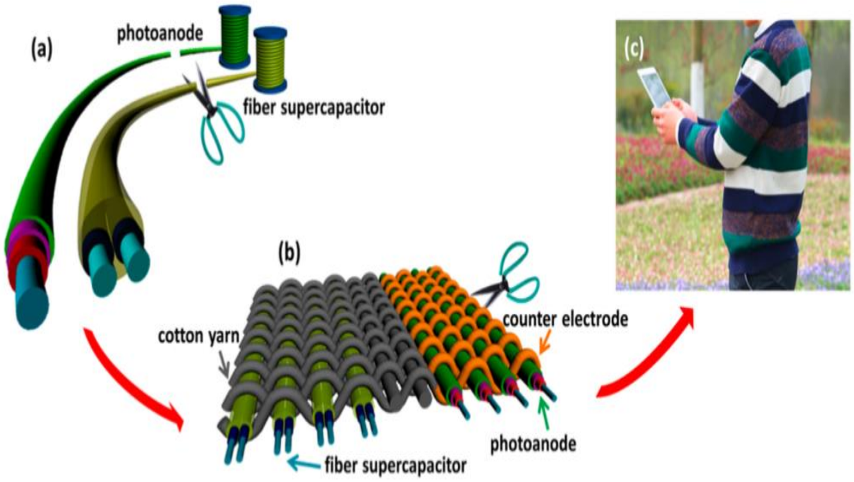
Looking around us we can see sheer numbers of different products from bendable smartphone and watches to biomedical skin-like devices, all show us that new era of wearable smart electronics has already started. Despite some attempts to produce wearable energy device which at the same time are light, the main hurdle in this area, energy harvesting devices production, is the sporadic characteristic of renewable energy. Among recent studies that have been done in producing simultaneous energy harvesting and storage systems, we can refer to fiber-shaped energy devices that have the ability to be woven into closes. Like cotton which goes through the process of spinning weaving, tailoring, and sewing from field to factory to make a garment, the same process but more challenging and complex one is here in producing of wearable energy textile, which have dual functions of energy harvesting and storage.[1]

Even though in this process tailorability is one of the most difficult parts, but it has been neglected. To provide different demands we should be able to cut the energy units, fiber/textile, of smart garments. It is crucial for both fiber weaving to form textile and to textile design to produce various designs and styles. In addition, tailorability allows us to repair the damaged parts, by cutting them and reconnecting the intact ones.[2,3]

In recent years FSCs or fiber supercapacitors due to their tailorability, flexibility, and knittability have been considered vastly by scientists as wearable energy storage.[4] The considerable electrical conductivity, 3125 −55000 S cm $^{-1}$, and high specific capacitance of pseudocapcitive TiN nanomaterials make them a promising candidate as electrodes in the supercapcitors. In addition, a photovoltaic cell, because of the availability of solar energy, is the best candidate for wearable and portable energy harvesting device. In scheme 1 you can see an all solid tailorable energy textile which combine solar energy harvesting and storage which is presented in the present study.

The new textile has the capability of being mass produced. This FSC could be tailored into different size and woven to produce textile. The authors fabricated an all solid-dye-sensitized solar cell (DSSC) textile using interweaving fiber shaped counter electrodes (CEs) and photoanodes. As you can see in scheme 1a, like FSCs, the photoanode which is coated with solid state electrolyte is also tailorable. This study shows a very useful way of producing wearable and tailorable energy textile devices.[1]

Scheme 1. Schematic of the Composition and Structure ("Thread to Cloth") of the Integrated Energy Textile for Future Smart Garments[a]



Key: (a) The "threads" ((FSC) or DSSC photoanode) which can be large-scale fabricated and tailored into various segments. (b)Textile energy device in which FSC and DSSC are integrated. (c) Future smart energy garment to power small electronics.[1]

Result and discussion

Fabrication process contains the following steps: in the first step the fiber electrode/device is made, which is a tailorable and flexible. In the second step, using industrial weaving loom the energy textile will be produced by weaving strings of fiber electrodes/devices. Electric series connections of the FSCs module allow it to be charged to several volts, the advantage that provides it with plenty of commercial applications.

The TiN NWs arrays that have high electrochemical performance are used in FSCs as active materials. TiN is coated with a very thin layer of amorphous carbon shell, to compensate weak cycling stability of TiN which arises from irreversible oxidation. The details are demonstrated in Figure 1a. first $H_2 Ti_2O_5\cdot H_2O$ NWs is obtained by alkali hydrothermal treatment and some extra ion exchange process; then carbon shell is coated using glucose-assisted hydrothermal deposition and subsequent carbonization, and to validate the formation of TiN NWs XRD, XPS, TEM and SEM methods have used. According to TEM analysis Porous TiN NWs are exhibited, which is cause both faster electron transportation and larger surface area, followed with high electrochemical performance such as increasing volumetric capacitance and charge/discharge rate.[1]

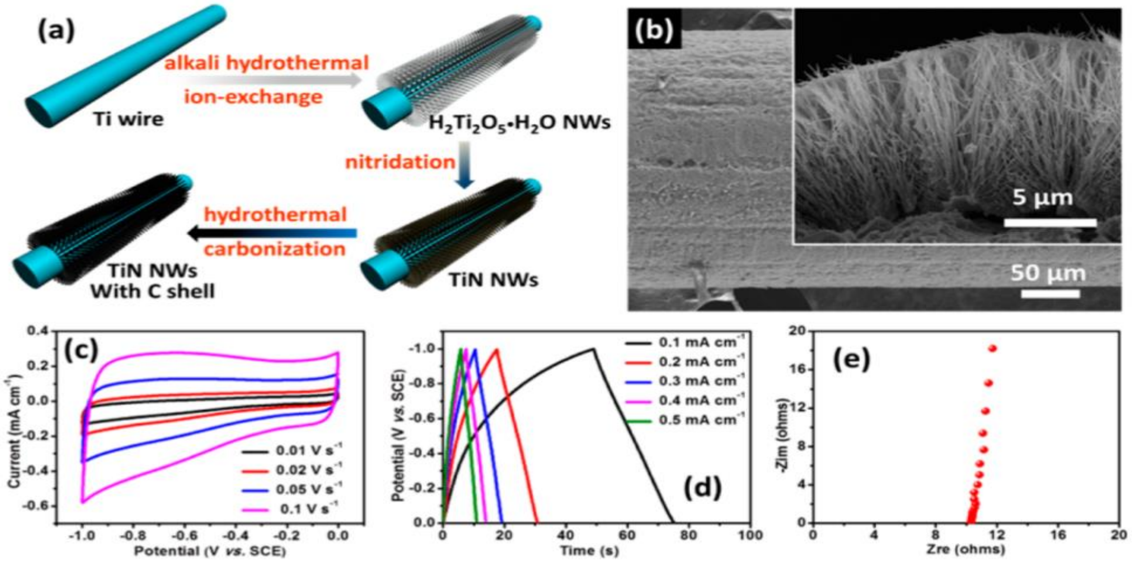


Figure 1. TiN nanowire based FSC electrode: (a) detailed synthesis process of TiN NWs on Ti wire; (b) panoramic view SEM image of the TiN/Ti wire and the cross-sectional view SEM image of TiN NWs; (c −e) electrochemical properties (CV curves, galvanostatic charge/discharge curves, and Nyquist plot) of the TiN/Ti wire with length of 2 cm.[1]

TiN NWs are coated with a very fine carbon shell acting as a protective layer thus, preventing its oxidization to TiO_2 when exposed to environment.[5] This coating resulted in small increase in capacitance, which can be observed in cyclic voltammetry curves at various scan rates (0.01 to 0.1 V s-1). A 4cm long SS FSC device (Figure 2a) was made by grouping two TiN electrodes. These electrodes are covered by KOH/PVA gel which separates the two electrodes and also acts as an electrolyte. This improves the capacitance response even at a 50 V s-1 scan rate (Figures 2b & 2c).

To study the rate capacity or capability of fiber super capacitors, correlation between the retention of capacitance and scan rate is measured. About 68% and 37% capacitance retention, was observed at 1 V s-1 and 10 V s-1 of scan rates. Further, in depth analysis of diffusion and capacitance of these FSC was performed in order to test its ability of fast-charging. TiN FSC exhibited high stability by maintaining a capacitance of about 87.5% at 0.05mA of current at 5000 cycles of GCD, which was not observed in the uncoated TiN NWs i.e, they show decrease in capacitance.

Weaving of textile involves a lot of bending and twisting, therefore the stability of FSCs is an important criteria in making of wearable energy storage fabric. TiN FSC has shown an excellent flexibility as well as stability without any decrease in the capacitance (maintaining ~98%) in CV curves at various bending angles. In order to check its practicability, a 20 cm long TiN FSC was made and its capacitance and stability was compared with a 4 cm long FSC using CV, which showed almost similar results supporting the possibility of mass production of the textile.

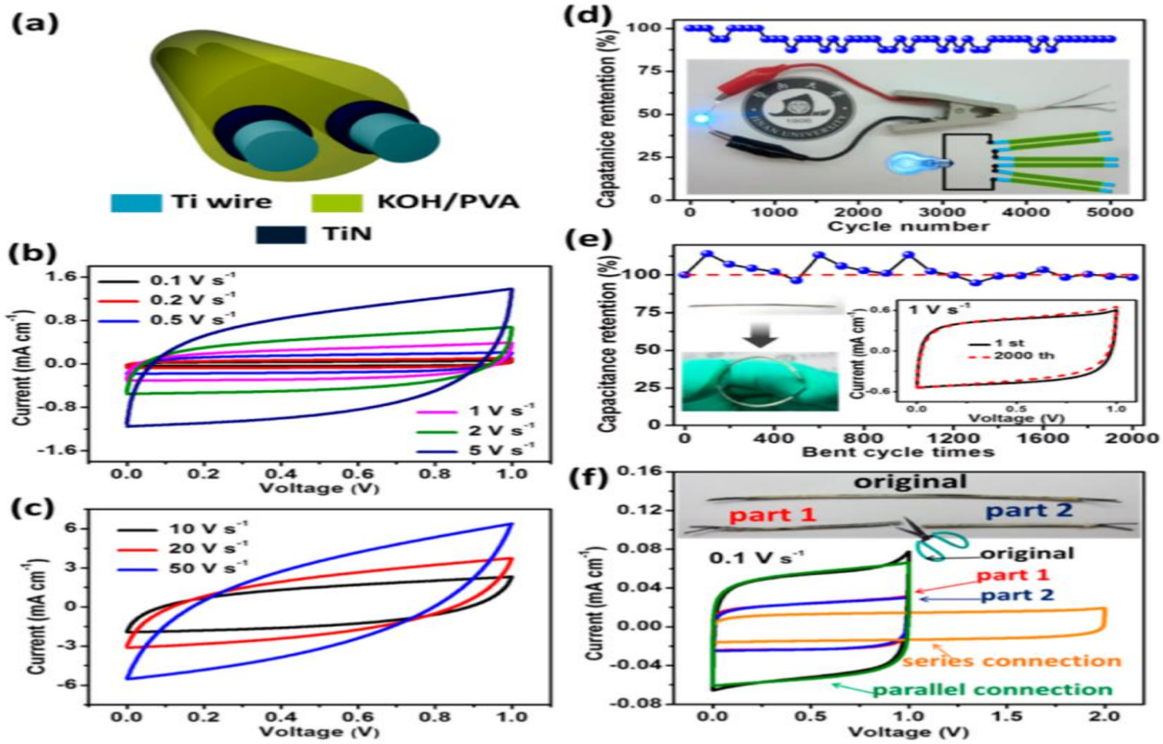


Figure 2. Solid-state FSC device: (a) schematic of the structure of TiN nanowire based FSC; (b, c) CV curves of the 4 cm long FSC at scan rates from 0.1 to 50 V s −1 ; (d) cycle performance at a current of 0.05 mA of the FSC (inset shows a blue LED lighted by three series connected FSCs); (e) capacitance retention under bent for 2000 times (from 0° to 360° for each cycle) and CV curves of the first and 2000th cycle (inset); (f) demonstration of the tailorability of the FSC.

In order to confirm the potential of the TiN FSC as an energy storage device, a series three FSCs are linked up together to power a led (Figure 2d). And to determine its tailorability, a 4 cm long FSC is cut into equal two parts, i.e., 2 cm each (Figure 2f). Each individual part has shown nearly half of the capacitance of the 4 cm one, thus indicating tailoring process barely affects the TiN FSCs performance.

The components for harvesting the solar energy (DSSC module) are woven by shuttle flying technique interlacing both CEs (Cu coated polymer wires) and fiber shaped photoanodes together (Figure 3a). These fiber-shaped photo-anodes are made by growing ZnO NWs on a polymer wire coated with Mn, which is sensitized by a dye and further coating these with a CuI transfer layer (Figure 3b). The performance of these components at various bending angles (0° to 120°) as shown in Figure 3e and 3f, were analyzed by using their photocurrent−voltage (I−V), and their flexibility and bending were analyzed using photo-current density-voltage (J−V), the performance of these was not altered even when the bending cycles were increased by 100, which proves the feasibility of using these DSSC textiles as energy storage devices. Even though the efficiency of power conversion is higher for liquid-electrolyte-based DSSC than solid-electrolyte based DSSC, which can be outlooked by the advantage of the tailorability.

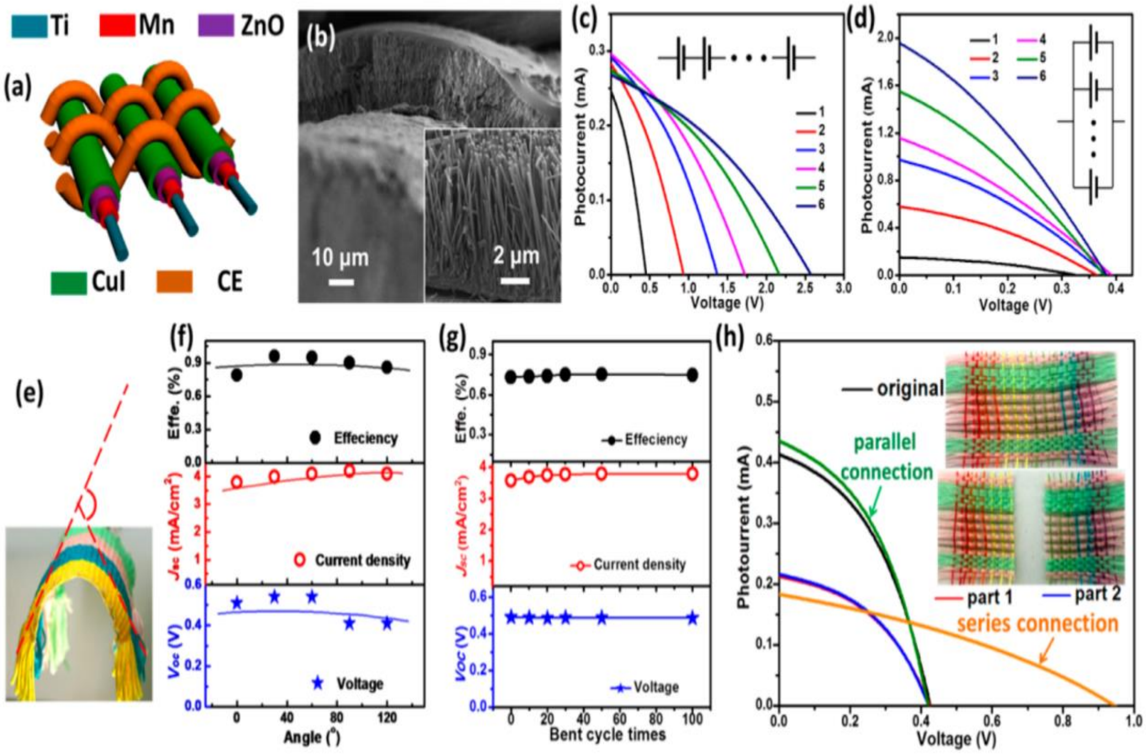


Figure 3. DSSC textile: (a) schematic of the interlaced structure of photoanode and CE; (b) cross-sectional view SEM image of the ZnO- nanorod based photoanode; (c, d) output performances of the DSSC textile with strings connected in series and parallel, respectively; (e−g) performance stability tests of the DSSC textile with different bending angle and bent times; (h) demonstration of the tailorability of the DSSC textile.

Furthermore, the experiments shows an excellent chemical stability of CuI-type all-solid DSSC textile. The performance was not decreased even when this textile was stored for about 2 months without any encapsulation. In order to prove the photo anodes are tailorable a DSSC fabric with I_{sc} of 0.41 mA and V_{oc} of 0.41 V is cut into two halves, each half maintaining ~0.21mA (nearly half of the main textile), the photo-electric performance was regained when the separated textiles are connected in parallel and a V_{oc} of 0.94 is attained when the same are connected in series. These show that DSSC textile has a capability of harvesting solar energy, which can be further improved by incorporating an energy storing ability.

The “thread to cloth” pattern was achieved by weaving FSCs and DSSCs together, with cotton yarns intervening side by side to make a light harvesting and storing energy textile. These patterns are possible because the weaving is done by flexible single threads of FSCs, fiber-shaped photoanodes and CEs (Fingure 4a). The ability of charging and discharging of energy textile is studied using nine photoanode strings of 4 cm each, divided into three groups with each connected in series. And in each group, the three photoanodes are connected in parallel, this resulted in increase V_{oc} to about 1.2V which is sufficient to charge the TiN FSC. Thus, the two parallel joined TiN FSCs work as energy storage space in the textile.

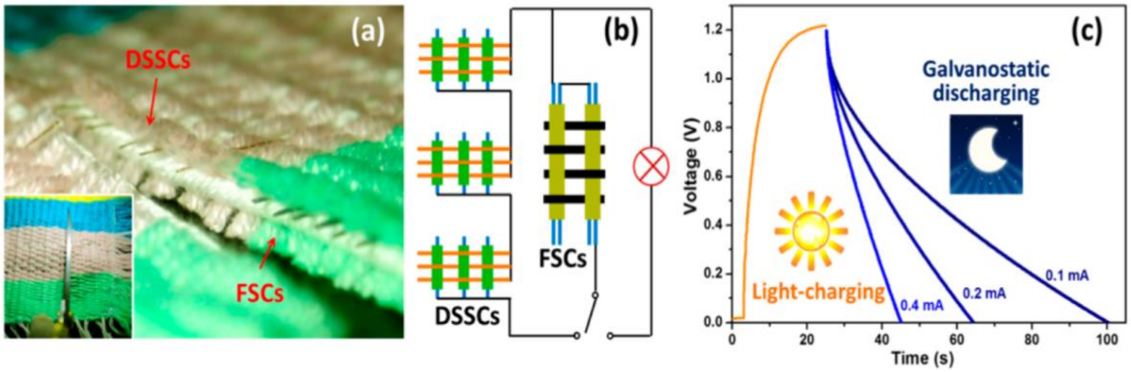


Figure 4. Integrated energy textile: (a) photographs showing the tailorability of the textile cloth which integrates DSSC and FSCs functions;(b) equivalent circuit; (c) light-charge and galvanostatic discharge performance.

The DSSC acts as a solar energy harvester, while the super capacitors as storage device upon exposure of this textile to light. The FSC module shows different charging rates under different light intensities, it can be charged to 1.2 V in 17 s. The discharging process is monitored by galvanostatic method using unvarying current density. It takes 78 s, 40 s and 20 s at a current of 0.1 mA, 0.2 mA, and 0.4 mA respectively, to completely discharge the FSC module, which rate can be further improved by increasing the photoanode length in DSSC module. All these results provide a vast platform for applicability of these textiles in the field of wearable electronics. The future area in the development of this textiles can be done by enhancing energy conversion as well as the storage performance.

Conclusion

In short, an integrated single layered smart garment which can simultaneously harvest the solar energy (ZnO-based DSSC) and store the harvested energy (by TiN-based FSC) was prepared. Both the DSSC and TiN FSC show superior stability, bending resistance, power conversion efficiency along with an excellent tailorability properties. Weaving of different patterns of wearable devices from a single layered versatile textile was possible without any loss in their performance providing a smart garment with enhanced user experience.

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