Polyaniline electrochemically deposited on tailored metal mesh for dynamically stretchable supercapacitors

Fangya Qi
Chen Zhao
cz995@uowmail.edu.au
Caiyun Wang
University of Wollongong, caiyun@uow.edu.au
Xiaoteng Jia
University of Wollongong, xj916@uowmail.edu.au
Li Weng

See next page for additional authors

Follow this and additional works at: https://ro.uow.edu.au/aiimpapers

Part of the Engineering Commons, and the Physical Sciences and Mathematics Commons

Recommended Citation
Qi, Fangya; Zhao, Chen; Wang, Caiyun; Jia, Xiaoteng; Weng, Li; He, Tingting; and Min, Yonggang, "Polyaniline electrochemically deposited on tailored metal mesh for dynamically stretchable supercapacitors" (2019). Australian Institute for Innovative Materials - Papers. 3959.
https://ro.uow.edu.au/aiimpapers/3959

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
Polyaniline electrochemically deposited on tailored metal mesh for dynamically stretchable supercapacitors

Abstract
© 2019 The Electrochemical Society. As power source for integrated wearable electronics, stretchable supercapacitors have gained significant attention. Here, an in-plane compression strategy is proposed to make highly stretchable current collectors from commercially available stainless steel mesh. Polyaniline is deposited on the compressed metal mesh to produce stretchable pseudo-capacitive electrode with 100% stretching deformation capability. An intrinsically stretchable supercapacitor is demonstrated using such electrodes and poly(vinyl alcohol)H3PO4 polymer gel electrolyte. The assembled supercapacitor shows an areal capacitance of 13.5 mF cm⁻² at a current density of 0.1 mA cm⁻². It can maintain 89% of its initial capacitance after 1000 stretching/releasing cycles at a high strain of 100%. It can also endure a dynamic stretching rate of 7.5% s⁻¹ with a capacitance retention of 92.9%. This work proves the potential of fabricating stretchable devices with commodity materials.

Disciplines
Engineering | Physical Sciences and Mathematics

Publication Details

Authors
Fangya Qi, Chen Zhao, Caiyun Wang, Xiaoteng Jia, Li Weng, Tingting He, and Yonggang Min

This journal article is available at Research Online: https://ro.uow.edu.au/aiimpapers/3959
Polyaniline Electrochemically Deposited on Tailored Metal Mesh for Dynamically Stretchable Supercapacitors

Fangya Qi a, Chen Zhao* a, z, Caiyun Wang b, Xiaoteng Jia b, Li Weng a, Tingting He a, Yonggang Min* a, z

a. School of Materials and Energy, Guangdong University of Technology, Guangzhou 510006, China

b. ARC Centre of Excellence for Electromaterials Science, Intelligent Polymer Research Institute, AIIM Facility, University of Wollongong, Wollongong, NSW 2522, Australia

Corresponding authors:

Chen Zhao: czhao@gdut.edu.cn

Yonggang Min: yong686@126.com
Abstract

As power source for integrated wearable electronics, stretchable supercapacitors have gained significant attention. Here, an in-plane compression strategy is proposed to make highly stretchable current collectors from commercially available stainless steel mesh. Polyaniline is deposited on the compressed metal mesh to produce stretchable pseudo-capacitive electrode with 100% stretching deformation capability. An intrinsically stretchable supercapacitor is demonstrated using such electrodes and poly(vinyl alcohol)-H$_3$PO$_4$ polymer gel electrolyte. The assembled supercapacitor shows an areal capacitance of 13.5 mF cm$^{-2}$ at a current density of 0.1 mA cm$^{-2}$. It can maintain 89% of its initial capacitance after 1000 stretching/releasing cycles at a high strain of 100%. It can also endure a dynamic stretching rate of 7.5% s$^{-1}$ with a capacitance retention of 92.9%. This work proves the potential of fabricating stretchable devices with commodity materials.

Keywords:

Stretchable, supercapacitor, polyaniline, compression, stainless steel mesh
Introduction

Stretchable electronics are devices that show minimal function loss under mechanical deformation. They can be attached to uneven and moving surfaces such as human body as functional wearable devices, and have attracted significant attention from both scientific and technological communities.\textsuperscript{[1]} To date, various stretchable electronics have been fabricated including transistors, polymer light-emitting diodes, and strain sensors.\textsuperscript{[2-4]}

The rising of stretchable electronics drives the development of power source devices that can sustain deformations without sacrificing their electrochemical performances.\textsuperscript{[5]} Supercapacitors (SCs) have been intensively studied as energy storage devices due to their higher power density, longer cycle life than batteries, and higher energy density than conventional dielectric capacitors.\textsuperscript{[6]} To achieve an intrinsically stretchable SC, each device component including electrodes, separator and electrolyte should be stretchable, especially the stretchable electrodes which determine the electrochemical performance. Currently, several electrode structures have been proposed including buckled, spring-like, textile, 3D porous, and mesh-like structures.\textsuperscript{[7-9]} Stretchable SCs based on the first four structures are mostly investigated and have achieved remarkable progress: SCs with buckled carbon nanotube/MnO\textsubscript{2} film electrodes and hydrogel electrolyte could be stretched up to 150\%;\textsuperscript{[10]} fiber shaped SCs with two fiber electrodes parallel-winded along a rubber core showed a maximum stretching ratio of 360\%;\textsuperscript{[11]} SCs assembled from poly(3,4-ethylenedioxythiophene) coated polyester fabric showed nearly no capacitance loss when being stretched up to
3D graphene foam based SCs could sustain a strain of 60% with slight capacitance decrease of 9%. Compared with these four electrode structures, metal mesh based stretchable electrodes possess advantages in easy fabrication and low cost. Metal nanomesh and macroscopic mesh have been utilized for assembling stretchable supercapacitors. Gold nanomesh based stretchable supercapacitor could sustain a strain of 100%, while the largest strain that macroscopic stainless steel (SS) mesh electrodes based SCs could sustain is reported to be only 20%. Therefore, it is highly desired to enhance the stretchability of macroscopic mesh electrodes from the engineering aspects.

Here, a facile in-plane compression method is proposed to enhance the stretchability of macroscopic mesh electrodes. Combining the smart tailoring and in-plane compressing, a highly stretchable conductive substrate can be obtained using commercially available and low cost SS mesh. When cutting along the diagonal direction of the woven SS mesh, the obtained SS mesh is not only stretchable but also compressible. By applying an in-plane compression, SS mesh with a stretchability of 100% can be obtained. Polyaniline (PANi) is then electrochemically deposited onto the compressed SS mesh to produce stretchable capacitive electrode. An intrinsically stretchable SC with 100% stretchability is demonstrated using such electrodes and poly(vinyl alcohol) (PVA)-H₃PO₄ polymer electrolyte. The stretchable SC shows stable electrochemical performance under both static and dynamic stretching states.

**Experimental**

**Materials**
Aniline (99.5%) was obtained from Shanghai Aladdin. PVA (Mw: 14, 6000-18, 6000, 99+% hydrolyzed) was purchased from Sigma-Aldrich. Sulfuric acid (H₂SO₄, 98%), phosphoric acid (H₃PO₄, 85%) and ethanol were obtained from Guangzhou chemical reagent factory. Aniline was freshly distilled, while all the other chemicals were used as-supplied. SS mesh (wire diameter 0.2 mm, aperture 0.7 mm) was commercially available from local steel screen market.

**Preparation of PVA- H₃PO₄ polymer gel electrolyte**

PVA-H₃PO₄ polymer gel electrolyte was prepared according to our previous report. Briefly, PVA (6.0 g) was added into deionized water (60 mL), and the mixture was heated to 90 °C with vigorous stirring until the solution became clear, followed by cooling down to room temperature. Then H₃PO₄ (9.0 g) was added into the PVA solution and stirred overnight to obtain the gel electrolyte.

**Preparation of stretchable mesh electrodes**

The SS mesh was cut along the diagonal direction to obtain stretchable and compressible strips with 16 mm width. These strips were treated with ethanol and diluted sulfuric acid to remove the surface impurities. Such strips were compressed by 33.3% using tweezers, and after compression, the width of the strips expanded to 20 mm. Then the compressed SS mesh was fixed on a frame which had an open area of 20×20 mm² for PANi deposition (Fig. S1). PANi was electrochemically polymerized onto the compressed SS mesh from the aqueous solution containing 0.1 M aniline and 1.0 M H₂SO₄ at a constant current of 0.8 mA for 10, 20 and 30 min. The electrodes were washed by water after deposition.
Fabrication of stretchable supercapacitor

Two pieces of electrodes were immersed into the gel electrolyte solution for 20 min, followed by leaving them in fume hood overnight for gel solidification. This process was repeated to ensure that the electrodes were fully covered by the gel electrolyte. A thin layer of electrolyte was cast on an electrolyte-coated PANi electrode as adhesion layer, and then it was pressed onto another electrolyte-coated PANi electrode face to face to form the supercapacitor. Finally, the supercapacitor was sealed with 3M VHB™ 4910 tape.

Characterization

Morphologies of the electrodes were characterized by a field-emission scanning electron microscope (Hitachi SU8010, Japan). Raman spectrum of PANI was obtained using a Raman spectrometer (Nost FEX-VS4, Korea) with 532 nm diode laser. Optical images of electrodes were acquired by an inverted fluorescence microscope (Olympus IX71, Japan). The resistance of SS mesh under stretching was measured by digital multimeter (Keysight 34465A, USA). Cyclic voltammetry (CV), galvanostatic charge–discharge (GCD) and electrochemical impedance spectroscopy (EIS) were measured on an electrochemical workstation (Chenhua CHI 760E, China). EIS was measured at the open circuit potential over the frequency range of 100 kHz to 0.01 Hz with potential amplitude of 5 mV. The electrochemical tests of electrodes under strains were performed by fixing them on a glass frame, while the supercapacitor devices were mounted on an automatic stretching platform (Zolix PSA200-11-X, China).

Areal specific capacitance ($C_{asp}$) of the stretchable supercapacitor can be calculated
from the CV curves using the following equation:\textsuperscript{[17]}

\[ C_{asp} = \frac{A}{2fVS} \]  \hspace{1cm} (1)

where \( A \) is the integral area of the CV loop, \( f \) is the scan rate, \( V \) is the potential window, and \( S \) is the area of the supercapacitor. The capacitance from the GCD curves can be obtained using the following equation:\textsuperscript{[18]}

\[ C_{asp} = \frac{I\Delta t}{S\Delta V} \]  \hspace{1cm} (2)

where \( I \) is the discharge current, \( \Delta t \) is the discharge time, \( \Delta V \) is the potential change after a full discharge, and \( S \) is the area of the supercapacitor.

Results and Discussion

The fabrication process of the mesh electrodes based stretchable supercapacitors is illustrated in Fig. 1. By cutting along the diagonal of the open squares of the SS mesh, stretchable and compressible conductive substrate was obtained. Then PANi was electrochemically polymerized on the compressed SS mesh (CSSM) to produce stretchable pseudo-capacitive electrodes. Finally, a stretchable supercapacitor device was assembled with gel electrolyte coated electrodes and sealed with elastic tape.

Metal meshes are usually woven from metal fibers and are commercially available in rolls. The most common metal mesh is SS mesh. It has been used as current collector for fabricating flexible supercapacitors.\textsuperscript{[19, 20]} The woven SS mesh is not stretchable along the weft or the warp as the SS wire is not stretchable. Nevertheless, it can be stretched or compressed along the diagonal direction of the weft and the warp. The strain applied to the tailored mesh was accommodated by the in-plane rotation of the weft and warp, similar to the motion of a scissors.\textsuperscript{[21]} As shown in Fig. 2a, the tensile
strain applied at the two ends of the tailored SS mesh electrode caused the transformation of the open squares to rhombuses. This manner endows the tailored SS mesh with intrinsic stretchability. This as-cut mesh electrode showed a cross weave angle of 90°, and it could be stretched to a maximum strain of ~33.3% with a reduced cross weave angle of ~40°. It is reported that the ability of a mesh structure to sustain the strain is a function of the cross weave angle: bigger angle leads to higher strain tolerance.[22] In this work, the cross weave angle can be easily enlarged through an in-plane compression strategy. The relation between maximum strain that the CSSM can endure ($S_{\text{max}}$) and the applied compressive strain ($S_{\text{compressive}}$) can be expressed as:

$$S_{\text{max}} = \left( \frac{1.333}{1 - S_{\text{compressive}}} - 1 \right) \times 100\% \quad (3)$$

As the mesh electrode was compressed by 33.3%, the cross weave angle was increased to ~125°, and a maximum strain of 100% could be achieved.

As a stretchable current collector, its conductivity should ideally keep steady under applied strain. The resistance changes of the CSSM (20×20 mm²) under different stretching levels was investigated (Fig. 2b). It was quite stable with a fluctuation of less than 0.5 Ω during the whole stretching process. The strain applied to the CSSM only caused the rotation of the SS wire other than stretching it. In addition, the resistance was almost unchanged compared to its initial state during 5000 stretching cycles at the 100% strain, evidencing the high durability of these CSSM electrodes (Fig. 2c). A simple circuit was constructed using the CSSM as connecting wire to illuminate a red LED. The CSSM worked well with strain up to 100% (Fig. 2d). All these results prove that the CSSM can work as robust stretchable current collector.
PANi was then electrochemically polymerized on the CSSM to produce capacitive electrode due to its good conductivity and high energy storage capability. Bare SS wire showed a rough surface (Fig. 3a), and after PANi deposition for 20 min, a thin layer of coral-like PANi nanowire networks was coated on the SS wire (Fig. 3b and 3c). Shortening or extending the deposition time to 10 or 30 min resulted in PANi nanowire networks with similar coral-like morphologies (Fig. S2). Raman spectrum (Fig. 3d) confirmed the formation of PANi. The peaks ascribed to PANi were found at 1589 cm\(^{-1}\) (\(\nu\) C-C of the benzene rings), 1470 cm\(^{-1}\) (\(\nu\) C=N of the quinoid nonprotonated di-imine units), 1394 cm\(^{-1}\) (polymer reticulation induced occurrence of tertiary nitrogen), 1317 cm\(^{-1}\) (\(\nu\) C-N\(^+\), characteristic peak of the polaron radical cation), 1221 cm\(^{-1}\) (\(\nu\) C-N of benzene diamine units), 1149 cm\(^{-1}\) (C-H bending of benzene), 805 cm\(^{-1}\) (out-of-plane C-H motions), 520 cm\(^{-1}\) and 415 cm\(^{-1}\) (out-of-plane C-N-C deformation). [24, 25]

To evaluate the electrochemical properties of the PANi/CSSM electrode, CV tests were carried out in a three-electrode system with a Pt foil counter electrode and a Ag/AgCl reference electrode in 1.0 M H\(_2\)SO\(_4\) electrolyte over the potential of -0.2 to 0.9 V (Fig. 4a-4c). CV curves of the PANi/CSSM electrode with different deposition time at different scan rates ranging from 10 to 100 mV s\(^{-1}\) displayed three pairs of redox peaks which were attributed to the transformations between different redox states of PANi. Redox peaks A\(_1\)/C\(_1\) corresponds to the redox transition of PANi between the leucoemeraldine and the emeraldine forms. The peaks A\(_2\)/C\(_2\) are assigned to the redox transition between \(p\)-benzoquinone and hydroquinone. Peaks A\(_3\)/C\(_3\) are ascribed to the
redox transition of PANi between the emeraldine and the pernigraniline forms.[26] The areal specific capacitances of the electrodes with different PANi deposition time are plotted in Fig. 4d. The areal specific capacitance increased with the extended deposition time. The electrode with 10 min of deposition exhibited an areal capacitance of 11.6 mF cm\(^{-2}\) at 10 mV s\(^{-1}\), and it was enhanced by more than 2.4 times to 39.6 mF cm\(^{-2}\) with 20 min of deposition. Increasing the deposition time to 30 min could lead to further improvement in capacitance. However, it increased by only 12.4% to 44.5 mF cm\(^{-2}\) compared with 20 min of deposition. 30 min of deposition could result in thicker PANi layer, but during the washing process after deposition, part of PANi was washed off from the SS mesh, resulting in limited enhancement in capacitance. Thus in the following tests, 20 min of deposition was chosen to prepare the stretchable electrodes. The PANi/CSSM electrode showed almost overlapped CV curves while it was stretched from 0 to 100% (Fig. S3), indicating the high stretchability. The strain only caused the deformation of the open squares of the mesh electrodes, other than stretching the PANi layer. The structures of PANi even near the joint position were well retained under 100% strain (Fig. S4a-b) and after 1000 stretching cycles (Fig. S4c-d).

Two PANi/CSSM electrodes were assembled into an intrinsically stretchable supercapacitor using PVA/H\(_3\)PO\(_4\) gel electrolyte, and the whole device was sealed with 3M VHB™ elastic tape. The electrochemical properties of the device were investigated by means of CV, GCD, EIS and cycling life tests. Fig. 5a shows the CV curves of the supercapacitor device at different scan rates ranging from 5 to 100 mV s\(^{-1}\) in the potential window of 0-0.8 V. The redox peaks were not obvious compared with the CV
curves of PANi/CSSM electrode, which is caused by the cell configurations. In a three-electrode system, only working electrode contains active materials, the potential applied to the working electrode is the whole range of the CV test. In a symmetrical two-electrode system, both electrodes contain active materials, and the potential applied to each electrode is the same and is half of the value of the potential range. Therefore, the current response in two-electrode system is different from that of three-electrode system.\[18\] Similar phenomenon can also be found in PANi/multi-walled carbon nanotubes based supercapacitor devices.\[27\] The device showed nearly rectangular CV responses at the scan rates up to 100 mV s\(^{-1}\), indicating that the processes were highly reversible. The areal specific capacitance was 13.0, 12.2, 11.3, 10.4 and 9.5 mF cm\(^{-2}\) at a scan rate of 5, 10, 25, 50 and 100 mV s\(^{-1}\), respectively, which is much higher than that of graphene based stretchable supercapacitors (4.27 μF cm\(^{-2}\) to 3.3 mF cm\(^{-2}\)).\[28-30\] The corresponding gravimetric specific capacitance of the device was 104, 97.5, 90.5, 83.3 and 75 F g\(^{-1}\) at a scan rate of 5, 10, 25, 50 and 100 mV s\(^{-1}\), respectively. In the case of a single electrode, its gravimetric specific capacitance was 416, 390, 362, 333 and 300 F g\(^{-1}\), respectively. This is comparable to the reported value of PANi which is in the range of 200-1000 F g\(^{-1}\)\[31\]. The reduced capacitance at high scan rates can be attributed to the insufficient redox reaction rate. The charge-discharge curves were found to be nonlinear (Fig. 5b), indicating the process of faradic reactions.\[32\] It delivered an areal specific capacitance of 13.5 mF cm\(^{-2}\) at a current density of 0.1 mA cm\(^{-2}\). At 1.0 mA cm\(^{-2}\), the value was retained as 11.4 mF cm\(^{-2}\) (Fig. 5c). As shown in the Ragone plot (Fig. 5d), the areal energy density reached 1.20 µWh cm\(^{-2}\) at a power density of 40 µW
cm$^2$, and still remained at 1.01 $\mu$Wh cm$^2$ at a power density of 400 $\mu$W cm$^2$. The energy and power densities are much higher than that of graphene based stretchable supercapacitors (maximum energy density of 0.27 nWh cm$^2$, and power density of 36.48 $\mu$W cm$^2$).[28] They are also comparable to pure PANi based solid-state supercapacitors (maximum energy density of 0.71 $\mu$Wh cm$^2$, and power density of 400 $\mu$W cm$^2$).[33] The Nyquist plot for the device is shown in Fig. 5e. The vertical line in the low frequency region indicated a good capacitive behavior of the device.[34] No semicircle at high frequencies was observed, reflecting the fast ion diffusion in the electrode.[35] The coral-like PANi nanowire networks facilitate the ion diffusion. The equivalent series resistance (ESR) of the device, which can be represented by the intercept point on the real axis at high frequency,[36] was about 2.6 $\Omega$. To further evaluate the cycling life of the device, GCD measurements were conducted at a current density of 0.4 mA cm$^2$ for 2000 cycles. The device maintained its capacitance at 66% of its initial value after 2000 charge-discharge cycles (Fig. 5f). The capacitance loss can be mainly attributed to the mechanical degradation of PANi caused by the volume change (swelling and shrinking) during the doping-dedoping process associated with charging/discharging cycles. After 2000 charge-discharge cycles, the ESR increased to ~6.0 $\Omega$, and the device exhibited a large charge transfer resistance of ~40 $\Omega$ (Fig. S5).

To test the stretchability and the influence of strain on the electrochemical performance of the device, CV tests were conducted at 10 mV s$^{-1}$ while the device was stretching to different levels. The CV curves (Fig. 6a) slightly changed as the device was stretched from 0 to 100%. The capacitance calculated from the CV curves
decreased by ~1% as the device was stretched to 100% (Fig. 6b). As shown in the Nyquist plots (Fig. 6c), the ESR of the device gradually increased from 2.6 to 6.3 Ω during the stretching process from 0 to 100%. No semicircle at high frequencies was observed even at a strain of 100%, indicating the fast ion diffusion was not affected by the strain. To further estimate the stretching stability, stretching–releasing tests from 0 to 100% for 2000 cycles at a speed of 2.5% s⁻¹ were performed on the device. The CV curves distorted gradually (Fig. 6d), which can be ascribed to the mechanical deformation of the electrode and electrolyte under continuous stretching. The device maintained 88% of its initial capacitance (Fig. 6e), suggesting outstanding stretching stability. After continuous stretching, the device showed an increased ESR (6.5 Ω) and a charge transfer resistance of ~6 Ω (Fig. 6f), which may be caused the degradation of the electrodes after repeated stretching.

The above results were obtained under static testing conditions, however, as power source for wearable electronics, it is necessary to examine the electrochemical performance under dynamical strains. In practical application, fluctuations in the output current signals may affect the performance of wearable electronics powered by those stretchable power sources. Therefore, dynamic deformation tests are necessary to evaluate the application potential of stretchable supercapacitors in wearable electronics. We further investigated the performance of the device under dynamic stretching and releasing at different strain rates. A maximum strain was set as 100% and the strain rates were varied from 1.25 to 7.5 % s⁻¹ during one CV test (Fig. 7a). The scan rate of the CV test was fixed at 10 mV s⁻¹ and the potential window was 0-0.8 V, so it cost 160
s to finish one CV cycle. Meanwhile, it took 80 s for the device to reach 100% at a
strain rate of 1.25 % s⁻¹, hence one stretching/releasing cycle was included in one CV
cycle. Consequently, two, four and six stretching/releasing cycles were included per
CV cycle at strain rates of 2.5, 5.0, 7.5 % s⁻¹, respectively. At a strain rate of 1.25 % s⁻¹,
the stretching/releasing synchronized with charging/discharging, the CV curve kept
smooth with slight distortion compared to that obtained from the device without strain
(Fig. 7b). As the strain rate continuously increased to 2.5 and 5.0 % s⁻¹, the CV curves
still maintained the shape and were not affected by the dynamic stretching (Fig. 7c and
7d). When the strain rate reached 7.5 % s⁻¹, the CV curve became fluctuant (Fig. 7e),
which may be caused by the deformation of the electrodes and polymer gel electrolyte.
The dynamic capacitance retentions of the device at different strain rates are plotted in
Fig. 7f. It showed 96.8%, 96.2%, 93.9% and 92.9% capacitance retention at strain rate
of 1.25, 2.5, 5.0 and 7.5% s⁻¹ without significant capacitance fade. The results presented
here revealed high deformation tolerance of our device. The cycling stability of the
device under dynamic strain rate of 5.0% s⁻¹ was tested at 0.4 mA cm⁻² for 1000 cycles
(Fig. S6). The capacitance retention decreased drastically to 11.9% after 1000 cycles,
which is much lower than that of device with no strain applied. The combination of
redox reaction and dynamic stretching caused severer degradation in the PANi
electrodes.

Bending tests were performed to further evaluate the mechanical tolerance of the
SC device. The device underwent small capacitance degradation when being bent to
180 degrees, which was evidenced by the minor distortion in the CV curves (Fig. S7a).
The capacitance retention was retained at 94% during the bending process from 0 to 180 degrees (Fig. S7b).

To demonstrate the practical application, three stretchable supercapacitors were connected in series to light a red LED. The charged series-connected devices successfully turned on the LED even at strain of 100% (Fig. 8), confirming the potential of our stretchable supercapacitor for powering electronics.

**Conclusions**

In summary, we have successfully proposed an in-plane compression strategy to convert commercially available stainless steel mesh to highly stretchable current collectors. This method provides a facile and cost-effective way to obtain conductive and stretchable substrates. The high stretchability is achieved through the deformation of the open squares in the mesh. To prove the concept, a highly stretchable capacitive electrode is prepared through electrochemical polymerization of polyaniline on the compressed mesh electrode. And an intrinsically stretchable SC is demonstrated using such electrodes and polymer gel electrolyte. The stretchable SC shows good static and dynamic deformation stability. The high strain tolerance can be attributed to the highly stretchable and conductive mesh substrates, elastic polymer electrolyte and packaging tape. Apart from conducting polymers, this system is also applicable to other materials that can be deposited through electrochemical route to produce highly stretchable energy devices, such as alkaline ion batteries and metal air batteries.

**Acknowledgements**
Financial supports from the Start-Up research grant of Guangdong University of Technology (220413181), and the Program for Guangdong Introducing Innovative and Enterpreneurial Teams (2016ZT06C412) are gratefully acknowledged.

References

Fig.1 Schematic illustration of the fabrication process for mesh electrodes based stretchable supercapacitor.
**Fig. 2** (a) Optical images of the tailored SS mesh under different deformation states. Resistance changes of the CSSM at different stretching levels (b) and after different stretching cycles (c). (d) Digital images of an red LED illuminated by using CSSM as the connecting wire under no strain and ~100% strain.
Fig. 3 SEM images of the SS wire in the mesh before (a) and after PANi deposition at low (b) and high (c) magnification. (d) Raman spectrum of PANi.
**Fig. 4** CV curves of PANi/CSSM electrode at different scan rates with PANi deposition time of 600 s (a), 1200 s (b) and 1800 s (c). (d) Areal specific capacitance of the PANi/CSSM electrode with different PANi deposition time calculated from CV curves.
Fig. 5 Electrochemical performance of the stretchable SC. (a) CV curves at different scan rates. GCD curves (b) and areal specific capacitances (c) at different current densities. (d) Ragone plot. (e) Nyquist plot. (f) Cycling performance at 0.4 mA cm$^{-2}$ for 2000 cycles.
Fig. 6 CV curves (a), capacitance retention (b) and Nyquist plots (c) of the SC at different stretching states. CV curves (d), capacitance retention (e), and Nyquist plots (f) of the SC after 2000 repeated stretching-releasing cycles from 0 to 100% at a speed of 2.5% s⁻¹.
Fig. 7 (a) Dynamic stretching at different strain rates to a maximum strain of 100%, and (b-e) the corresponding CV curves. (f) Capacitance retention of the supercapacitor at different dynamic strain rates.
Fig. 8 Digital images of three series-connected supercapacitors powering a red LED before and after being stretched to 100%.