Nitrogen-doped reduced graphene oxide intertwined with V$_2$O$_3$ nanoflakes as self-supported electrodes for flexible all-solid-state supercapacitors

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Flexible all-solid-state supercapacitors (SCs) have great potential applications in flexible and wearable electronics because of their safety, high power density, flexibility, and portability. Herein, a self-supported film electrode comprising nitrogen-doped reduced graphene oxide intertwined with vanadium trioxide nanoflakes (V$_2$O$_3$/N-rGO) was fabricated. The V$_2$O$_3$ nanoflakes have abundant active sites accessible to charge storage, and nitrogen-doped reduced graphene oxide provides a flexible support. The V$_2$O$_3$/N-rGO film electrodes exhibit high conductivity, short diffusion length for ions and electrons, and robust flexibility, resulting in excellent capacitive properties and flexibility. The flexible V$_2$O$_3$/N-rGO film electrode has a high areal capacitance of 216 mF cm$^{-2}$ at a current density of 1 mA cm$^{-2}$. All-solid-state flexible SCs assembled by sandwiching two self-supported V$_2$O$_3$/N-rGO hybrid electrodes with alkaline poly(vinyl alcohol) (PVA) and LiCl gel electrolyte show an ideal volumetric capacitance of 8.1 F cm$^{-3}$, an energy density of 0.55 mW h cm$^{-3}$, and a power density of 0.035 W cm$^{-3}$ at a current density of 0.1 A cm$^{-2}$, based on the entire cell. This indicates that the self-supported V$_2$O$_3$/N-rGO film electrodes have great potential applications in portable and wearable flexible electronics due to their high capacitance, high energy/power density, and good mechanical flexibility.

1. Introduction

The flexible and wearable electronic products such as bendable mobiles phones, flexible sensors, and wearable devices have gained intense research focus due to the increasing demand of flexible energy storage devices in our daily life. An ideal flexible supercapacitor should not only provide a flexible, lightweight, easily portable, and environmentally friendly power source, but also possess excellent electrochemical properties including a fast charge-discharge rate, high power density, and long cyclic life. Thus, the electrochemical properties of the flexible SCs should not be affected by the mechanical actions such as folding, bending, and other deformation actions. To fulfill these requirements, the key is to design a flexible electrode with robust mechanical strength and high capacitance because the electrode materials are the key components of SCs.

Generally, SCs can be classified into electrical double-layer capacitors (EDLC) and pseudocapacitors based on the charge storage mechanism. The charge storage of EDLCs is achieved via reversible ion adsorption/desorption on a large-surface-area that usually produce limited specific capacitance. The electrode materials such as carbon nanotubes and graphene usually provide low specific capacitance. In addition, the pseudocapacitors store charge through a fast reversible faradaic process of redox reactions, which may provide higher specific capacitance. Pseudocapacitive materials such as transition metal oxides [MnO$_2$,$^{5,6}$ NiO,$^7$ Co$_3$O$_4$,$^8$ Fe$_2$O$_3$,$^9$ MoO$_3$,$^{10}$ and V$_2$O$_5$ (ref. 11)] and conducting polymers including polypyrrole$^{12}$ and polyaniline$^{13}$ can deliver higher capacitance than carbon materials. However, the low electron conductivity of metal oxides and kinetic irreversibility associated with conducting polymers lead to a low rate capability and cycling stability. In recent years, transition metal carbides or nitrides have been demonstrated as electrode materials for SCs due to their high electrical conductivity, impressive specific capacitance, and chemical stability.$^{14-18}$ However, the synthesis of transition metal carbides or nitrides usually require high temperature and long reaction times, which do not meet the requirements for green synthesis methods.

Thus, capacitor materials with the good conductivity and high specific capacitance as well as fabricated using green synthesis methods are highly desired. Fortunately, vanadium-based oxide phases of V$_2$O$_3$ exhibit quasi-metallic conductivity of $10^3$ $\Omega^{-1}$ cm$^{-1}$, close to that of Ru$_2$O$_3$.$^{19}$ Therefore, V$_2$O$_3$, as well
as VN, may also be a great candidate to develop fast ECs with high-power and high-energy densities. Li et al. have reported that V$_2$O$_5$@C composites exhibit a specific capacitance of 205 F g$^{-1}$ at 0.05 A g$^{-1}$ over a potential range of $-0.4$ to $-0.6$ V.\textsuperscript{29} However, a graphene-bridged V$_2$O$_5$/VO$_x$ core–shell electrode was fabricated by Xuan Pan, which exhibited a specific capacitance of 590 F g$^{-1}$ at 5 mV s$^{-1}$ and high-power and high-energy densities.\textsuperscript{30} The reason is that V$_2$O$_5$ has a high conductivity, and V$_2$O$_3$/VO$_x$ core–shell structure provides high capacitance. Hence, V$_2$O$_5$ could be a great candidate for developing fast supercapacitors with excellent electrochemical performance.

Herein, we report the synthesis of nitrogen-doped reduced graphene oxide intertwined with V$_2$O$_3$ nanoflakes to form a self-supported film electrode suitable for flexible all-solid-state SCs. The flexible self-supported V$_2$O$_3$/N-rGO film electrode comprised nitrogen-doped reduced graphene oxide intertwined with V$_2$O$_3$ nanoflakes (V$_2$O$_3$/N-rGO) without the introduction of any mechanical support or foreign binder. The flexible V$_2$O$_3$/N-rGO film electrodes have several advantages to achieve high electrochemical performance. First, the V$_2$O$_3$ nanoflakes provide more active sites accessible to charge storage, leading to high specific capacitance. In addition, nitrogen-doped reduced graphene oxide also participates in charge storage. Second, nitrogen-doped reduced graphene oxide intertwined with V$_2$O$_3$ nanoflakes has a robust mechanical structure, which is compatible with the intrinsic rigidity of V$_2$O$_3$, leading to robust flexibility and mechanical integrity of the V$_2$O$_3$/N-rGO film. Third, the interconnected framework of the V$_2$O$_3$/N-rGO film electrodes provide high conductivity and short diffusion length for ions and electrons, resulting in impressive capacitance. Fourth, the contact between V$_2$O$_3$ and N-rGO results in a much higher contact area at the interface, which can be beneficial for good dispersion without size variation or any agglomeration and retaining the structure during the charge–discharge process, which can help in achieving excellent cycling stability.\textsuperscript{21–24} As a consequence, the self-supported V$_2$O$_3$/N-rGO film electrodes deliver a high areal capacitance of 216 mF cm$^{-2}$ at a current density of 1 mA cm$^{-2}$. The all-solid-state flexible SCs fabricated by sandwiching two self-supported film electrodes with a LiCl/PVA gel electrolyte show an ideal volumetric capacitance of 8.1 F cm$^{-3}$ at a current density of 0.1 A cm$^{-3}$, a high energy density of 0.55 mW h cm$^{-3}$ at a power density of 0.035 W cm$^{-3}$, and excellent cycling stability. These values are higher than most of the previously reported results obtained from quasi and all-solid-state flexible SCs, demonstrating the great commercial potential of the present all-solid-state flexible SCs in portable or wearable devices.

2. Experimental

2.1 Preparation of the V$_2$O$_5$ gel

All chemical reagents were purchased and used without further purification. The flaky V$_2$O$_5$ xerogel was prepared using a typical hydrothermal method. For example, 0.24 g of V$_2$O$_5$ powder was dispersed in 20 mL of H$_2$O followed by the addition of 10 mL of H$_2$O$_2$ (30\%) under vigorous stirring for 2 h.\textsuperscript{25} The obtained orange solution was transferred to a 50 mL Teflon-lined autoclave. The autoclave was sealed and heated in an oven at 205 °C for 16 h. Finally, the brownish red gel was obtained.

2.2 Fabrication of the self-supported V$_2$O$_3$/N-rGO hybrid film

The flexible self-supported hybrid films were fabricated using a vacuum filtration method. First, the desired GO powders were sonicated in 15 mL of DI water for 60 min using a probe sonicator. Then, the desired V$_2$O$_5$ gel was added dropwise to the GO suspension and sonicated for 30 min to ensure sufficient mixing of the materials. The suspension was filtered through a filter membrane (220 nm pore size). After vacuum drying at 70 °C for 60 min, the self-supported V$_2$O$_5$ gel/GO hybrid film was peeled from the filtration membrane and was further annealed at 500 °C for 30 min under an NH$_3$ atmosphere to obtain the self-supported V$_2$O$_3$/N-rGO hybrid film. For comparison, the V$_2$O$_3$/N-rGO hybrid films were prepared by the annealing of V$_2$O$_5$ gel/GO films (with various mass ratios of V$_2$O$_5$ gel and GO) under an NH$_3$ atmosphere via the same procedure.

2.3 Fabrication of the half-cell and flexible all-solid-state symmetric devices

To optimize the electrochemical performance of the V$_2$O$_3$/N-rGO electrodes, the V$_2$O$_3$/N-rGO electrodes were investigated using three-electrode cells because they were simple and maneuverable. In the three-electrode configuration, the cell was equipped with V$_2$O$_3$/N-rGO as the working electrode, a saturated SCE as a the reference electrode, and a Pt plate as the counter electrode in a 1 M Na$_2$SO$_4$ electrolyte. All the all-solid-state supercapacitor devices studied for material performance in this study were fabricated using a two-electrode standard method. The LiCl/PVA gel was prepared as follows: 3 g of PVA was mixed with 30 mL of LiCl (5 M) aqueous solution and heated at 85 °C for 1 h under vigorous stirring.\textsuperscript{26} Herein, two pieces of the self-supported V$_2$O$_3$/N-rGO hybrid electrodes with a separator were sandwiched with LiCl/PVA gel as the solid-state electrolyte. Prior to assembly, the two self-supported V$_2$O$_3$/N-rGO hybrid electrodes and separator were immersed in the LiCl/PVA solution for 10 min. The devices were solidified at room temperature for 1 h and then placed under 40 °C and vacuum conditions to remove excess water.

2.4 Characterization

The morphology, structure, and composition of the samples were determined via field-emission scanning electron microscopy (FE-SEM, FEI, Nova 450 Nano), high-resolution transmission electron microscopy (HRTEM, TECNAI), X-ray diffraction using Cu K$_x$ radiation ($\lambda = 1.5418$ Å) (XRD, Philips, X’ Pert Pro), and XPS (ESCALB MK-II).

2.5 Electrochemical measurements

The three-electrode set-up in 1 M Na$_2$SO$_4$ used for the single electrode tests comprised Hg/Hg$_2$SO$_4$ and platinum flake as the reference and counter electrodes, respectively. The mass loading of the active materials in each electrode was 1.05 mg
cm$^{-2}$. The electrochemical performances of the V$_2$O$_3$/N-rGO hybrid electrodes and all-solid-state symmetrical devices were tested using an electrochemical station (CHI 660E). The areal capacitance $C_a$ (mF cm$^{-2}$), volumetric capacitance $C_{vol}$ (F cm$^{-3}$), energy density $E$ (mW h cm$^{-3}$), and power density (mW cm$^{-2}$) were calculated using the following equations:\textsuperscript{16}

\begin{align}
C &= I\Delta t/\Delta E \\
C_a &= C/S = I\Delta t/S\Delta E \\
C_v &= C/I = I\Delta t/V\Delta E \\
E &= CU^2/2V \\
P &= E/t
\end{align}

where $C$ is the total capacitance, $C_a$ is the area capacitance, $C_v$ is the volumetric capacitance, $S$ (cm$^{-2}$) is the effective electrode area, $I$ (A) is the charging/discharging current, $\Delta t$ (s) is the discharging time, $\Delta E$ (V) is the potential window during the discharging process after the IR drop, $A$ (cm$^{-3}$) is the volume of the entire device including the electrolyte and electrodes, and $U$ (V) is the operating voltage.

3. Results and discussion

Fig. 1 demonstrates the fabrication process of the flexible V$_2$O$_3$/N-rGO film electrodes and the flexible all-solid-state SCs. First, the GO powders were sonicated in DI water and the V$_2$O$_5$ xerogel was synthesized using a hydrothermal method.\textsuperscript{25} Then, a mixture of the GO suspension and V$_2$O$_5$ xerogel was obtained via ultrasonication. Second, the freestanding V$_2$O$_3$ xerogel/GO films were obtained by vacuum filtering the mixture and subsequently peeled off from the filter membrane after drying at 70 °C for 1 h. Finally, the flexible V$_2$O$_3$/N-rGO hybrid films were produced by thermally annealing the V$_2$O$_3$ xerogel/GO films at 500 °C for 30 min under an NH$_3$ atmosphere. The all-solid-state flexible SCs based on two symmetrical V$_2$O$_3$/N-rGO hybrid film electrodes were assembled using the LiCl/PVA gel electrolyte.

The XRD pattern of the product obtained by annealing the V$_2$O$_3$ xerogel and the freestanding V$_2$O$_3$ xerogel/GO film in an NH$_3$ atmosphere at 500 °C for 30 min is presented in Fig. 2. The XRD pattern of the product obtained by annealing V$_2$O$_3$ xerogel can be well attributed to the hexagonal structure of V$_2$O$_3$ (JCPDS no. 34-0187), as shown in Fig. 1a.\textsuperscript{26} For the composites obtained by annealing V$_2$O$_3$ xerogel/GO, the XRD pattern shows the features of board peaks above a diffuse background, indicating a poor crystalline quality (Fig. 1b). The XRD diffraction peak at 26° corresponds to N-doped reduced graphene oxide\textsuperscript{26} (See XPS characterization). The other diffraction peaks can be indexed to the hexagonal structure of V$_2$O$_3$ (JCPDS no. 34-0187). This suggests that the V$_2$O$_3$ xerogel and GO in the V$_2$O$_3$ xerogel/GO film after thermal treatment produce V$_2$O$_3$ and N-rGO, respectively. In addition, the diffraction peaks of V$_2$O$_3$ are broadened due to the doping of N-rGO. This indicates that V$_2$O$_3$/N-rGO was obtained by annealing the V$_2$O$_3$ xerogel/GO film under an NH$_3$ atmosphere at 500 °C for 30 min.

Fig. 3a shows the SEM images of the self-supported V$_2$O$_3$/N-rGO film. It can be observed that the surface of the film shows a wrinkled structure due to GO and graphene-like V$_2$O$_3$ xerogel. The cross-section SEM image shows that the self-supported V$_2$O$_3$/N-rGO film has a thickness of about 20 μm, and the V$_2$O$_3$ nanosheets intertwined with N-rGO nanosheets were uniformly distributed in the self-supported V$_2$O$_3$/N-rGO film (Fig. 3b). The V$_2$O$_3$/N-rGO film was further characterized by TEM and HR-TEM. The TEM images depicted in Fig. 3c show that the composite has a wrinkled structure due to the N-rGO nanosheets. The nanosheets are clearly observed in Fig. 3c. Fig. 3d indicates that the V$_2$O$_3$ nanosheet is a single-crystal, and the lattice fringe spacing is 0.205 nm, which is consistent with the spacing of the (202) plane of V$_2$O$_3$. In addition, N-rGO becomes disorientated due to the structural distortions caused by the intercalation of the nitrogen atoms into its graphitic plans.\textsuperscript{26} This provides more information about the V$_2$O$_3$/N-rGO composite structure.
To further investigate the V$_2$O$_5$/N-rGO sample, Raman spectroscopy was conducted to characterize the composition (Fig. 4). The Raman peaks at 1355 and 1588 cm$^{-1}$ originate from N-doped reduced graphene oxide. The Raman peaks at 645, 901, and 990 cm$^{-1}$ were attributed to VO$_x$ (ref. 25, 27 and 28) in the V$_2$O$_5$ sample. The reason is that the surface of V$_2$O$_5$ is naturally oxidized to V$^{4+}$ and V$^{5+}$ under ambient conditions. This indicates that the Raman spectra of the V$_2$O$_5$/N-rGO composites exhibit little V$^{4+}$ and V$^{5+}$ coated on V$_2$O$_5$ and the characteristic peaks of N-doped reduced graphene oxide.

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![Fig. 3](image-url) (a) and (b) SEM images of the V$_2$O$_5$/N-rGO samples. (c) and (d) TEM and HR-TEM images of the V$_2$O$_5$/N-rGO samples, respectively.

![Fig. 4](image-url) The Raman spectra of the N-rGO/V$_2$O$_5$ samples.

![Fig. 5a](image-url) Fig. 5a is the spectra of the typical XPS survey scans of the NH$_3$-treated graphene–vanadium oxide xerogel composites, in which C, N, O, and V can be apparently identified. The XPS survey spectra indicates that V$_2$O$_5$/N-rGO contains only C, V, N, and O graphite-like sp$^2$ C, N-sp$^2$ C, and N-sp$^3$ C corresponding to 284.9, 286.7, and 287.7 eV, respectively. In addition, most of the C atoms in the N-doped graphene are arranged in
a conjugated honeycomb lattice without other detectable impurities on their surface. Fig. 5b compares the high-resolution C 1s XPS spectra of the samples. It indicates that the carbon element of the sample originates from the main peak at 284.9 eV. The high-resolution N 1s spectra show five different states (Fig. 5c). The peak at 397.0 eV was attributed to the N atom from vanadium oxynitride (P1). The other three peaks at 398.3, 400.1, and 401.7 eV were ascribed to pyridinic nitrogen, pyrrolic nitrogen, and quaternary nitrogen in the outer shell. The high-resolution V 2p XPS peak in Fig. 5d shows the four chemical states of V: the peak at 515.0 eV was attributed to V–N–O\(^{4-}\) and the peaks at 516.0, 516.9, and 517.6 eV were attributed to V\(^{3+}\), V\(^{4+}\), and V\(^{5+}\), respectively. The existence of V\(^{4+}\) and V\(^{5+}\) in the V\(_2\)O\(_3\)/N-rGO samples is a result of the inevitable oxidation of surface V\(_2\)O\(_3\) when it is exposed to air.\(^{19}\)

The electrochemical properties of the flexible V\(_2\)O\(_3\)/N-rGO films were evaluated using a three-electrode system in a 1 M Na\(_2\)SO\(_4\) aqueous electrolyte with Hg/Hg\(_2\)SO\(_4\) as the reference electrode and Pt plate as the counter electrode. Fig. 6a shows the CV curves obtained for the electrodes with various ratios of \(V/G = 1\), \(V/G = 2\), and \(V/G = 3\) at a scan rate of 50 mV s\(^{-1}\). The CV curve obtained for the V\(_2\)O\(_3\)/N-rGO film electrode (\(V/G = 1\)) was close to rectangular in shape at a potential of \(-0.2\) to 0.6 V. In addition, the CV area of the V\(_2\)O\(_3\)/N-rGO film electrode (\(V/G = 3\)) is the greatest among all the samples, revealing its great specific capacitance. Herein, the flexibility of the film becomes poor for the \(V/G = 4\) electrode; thus, the optimal ratio of \(V/O\) for the V\(_2\)O\(_3\)/N-rGO film electrodes was determined to be 3. Fig. 6b indicates the most specific capacitance of the flexible V\(_2\)O\(_3\)/N-rGO films electrode (\(V/G = 3\)) in the potential range between \(-0.2\) and 0.6 V at a scanning rate ranging from 10 to 200 mV s\(^{-1}\). The galvanostatic charge–discharge (GCD) curves exhibit a slight curvature and symmetrical triangular shape without evident voltage drops between 1 and 10 mA cm\(^{-2}\), suggesting good pseudocapacitive behavior. The flexible freestanding V\(_2\)O\(_3\)/N-rGO electrode shows a substantial areal capacitance of 216 mF cm\(^{-2}\) (206 F g\(^{-1}\) based on the entire mass of the electrode) at a current density of 1 mA cm\(^{-2}\) (Fig. 6c). It is higher than the previously reported results: MVN@VN NWs electrode (196 F g\(^{-1}\) at 1.44 mA cm\(^{-2}\)),\(^{14}\) Fe\(_2\)O\(_3\) nanotube-based electrodes (180.4 mF cm\(^{-2}\) at 1.1 mA cm\(^{-2}\)),\(^{30}\) self-supported mesoporous VN/CNTs hybrid electrode (178 mF cm\(^{-2}\) at 1.1 mA cm\(^{-2}\)),\(^{31}\) MMNNBs/rGO hybrid electrode (142 mF cm\(^{-2}\) at 1 mA cm\(^{-2}\)),\(^{32}\) and hydrogenated ZnO core/shell nanoscale electrodes (138.7 mF cm\(^{-2}\) at 1 mA cm\(^{-2}\)).\(^{22}\) Moreover, 55% of the capacitance was retained when the current density was increased 10 times from 1 to 10 mA cm\(^{-2}\). This indicates that the V\(_2\)O\(_3\)/N-rGO electrode suffers from severe capacitance decay because of the solubility of V\(_2\)O\(_3\) during the process of the electrochemical measurements. Thus, the electrolyte becomes slightly yellow due to the formation of V\(^{5+}\).

The self-supported V\(_2\)O\(_3\)/N-rGO film electrode has good flexibility, high specific capacitance, low rate capability, and low cycling stability, caused by the solubility of V\(_2\)O\(_3\) in the aqueous solution system. However, the high solubility can be improved using a solid-state electrolyte. Thus, the self-supported V\(_2\)O\(_3\)/N-rGO film electrode is a promising candidate for high performance flexible SCs. To meet the practical requirements of a flexible electrode, a flexible all-solid-state SC composed of two self-supported V\(_2\)O\(_3\)/N-rGO film electrodes and a LiCl/PVA gel electrolyte was assembled, as illustrated in Fig. 1. Fig. 7a depicts the CV curves obtained for the assembled V\(_2\)O\(_3\)/N-rGO/V\(_2\)O\(_3\)/N-rGO symmetrical devices in the voltage range of 0 to 0.7 V at the scanning rates between 10 and 500 mV s\(^{-1}\). The CV curves exhibit a nearly rectangular shape and mirror image with respect to the zero-current line, even at a large scanning rate from 100 to 500 mV s\(^{-1}\), indicating superior capacitive behavior and high rate capability. The GCD curves obtained for the all-solid-state SCs at various current densities from 0.1 to 0.5 A cm\(^{-2}\) are shown in Fig. 7b. The capacitance of the devices was calculated to be 8.1 and 6.9 F cm\(^{-2}\) at the current density of 0.1 and 0.5 A cm\(^{-2}\), respectively. These values are higher than those for the previously reported flexible solid-state SCs such as hydrogenated ZnO@MnO\(_2\)/Fe\(_2\)O\(_3\) asymmetrical SCs (1.21 F cm\(^{-2}\) at 6.3 mA cm\(^{-3}\)),\(^{12}\) functionalized carbon-nanotube-based
SCS (3.0 F cm⁻³ at 0.133 mA cm⁻³), N-rGO-based SCs (3.4 F cm⁻³ at 20 mA cm⁻³), and a free-standing mesoporous VN/CNTs film electrode-based SCs (7.9 F cm⁻³ at 25 mA cm⁻³). Moreover, the device had superior rate capability with 76% capacity retention when the current density was varied from 0.1 to 1 A cm⁻³ (Fig. 7c). The electrochemical impedance spectra of the solid-state devices are presented in Fig. 7d. The Nyquist plot exhibits a nearly vertical line along the imaginary axis in the low frequency region, and the equivalent series resistance of the devices was about 5 Ω cm², revealing the excellent capacitor behavior of the device. The energy density E and power density P are the key parameters for the flexibility of the SCs in practical applications. Herein, the E and P values of the all-solid-state SCs were calculated and are listed in Fig. 7e. The E and P values of other previously reported devices are also presented in Fig. 7e for comparison. The volumetric energy density (0.55 mW h cm⁻³) of the devices described in this study is higher than that of some previously reported devices constructed from quasi and all-solid-state SCs such as carbon nanotube-based SCs H-ZnO NW-based SCs (0.04 mW h cm⁻³, PVA/LiCl), carbon microfiber bundles coated with multi-walled CNT-based SCs (0.14 mW h cm⁻³, PVA/H₂PO₄), carbon/MnO₂ core–shell fiber-based SCs (0.22 mW h cm⁻³, PVA/H₂PO₄), and H–TiO₂/MnO₂//H–TiO₂/C-based SCs (0.3 mW h cm⁻³, PVA/LiCl). The all-solid-state device based on the V₃O₅/N-rGO film electrode and a LiCl/PVA gel electrolyte exhibited remarkable long-term cycling stability at a current density of 1 A cm⁻³, and there was only a 19% decrease in the capacitance after 10 000 cycles, as presented in Fig. 7f, indicating its relatively high stability. Thus, the all-solid-state SCs exhibit excellent energy storage performance due to the excellent capacitive properties of the self-supported V₃O₅/N-rGO film electrode coupled with the matching PVA/LiCl gel electrolyte.

To evaluate the potential of our devices as flexible energy storage components in flexible/wearable electronics, CV tests were performed under different bending conditions. Fig. 8a exhibits no obvious change in the CV curves obtained under various bending conditions of 45°, 90°, 135°, and 180°, revealing the excellent flexibility. To further demonstrate the feasibility, three identical devices were connected in series or parallel to construct devices. The three units were denoted as A, B, and C, respectively. The charging/discharging voltage window of the three devices connected in series was 2.1 V with almost the same discharging time as a single device. The
charging time of the three devices in parallel was about 2.82 times longer than that of a single device, which is close to the theoretical value of 3, thereby conforming to the theorem of series and parallel connections of capacitors (Fig. 8b). This demonstration indicates the great potential of the V_{2}O_{3}/N-rGO film electrodes for practical applications in flexible electrochemical energy-storage devices.

4. Conclusions

In summary, a self-supported V_{2}O_{3}/N-rGO film electrode comprising nitrogen-doped reduced graphene oxide intertwined with V_{2}O_{3} nanoflakes was prepared using a facile and effective method; this method consisted of the hydrothermal formation of V_{2}O_{3} xerogel with subsequent mixing with a GO suspension, vacuum filtration, and annealing under an NH_{3} atmosphere. The V_{2}O_{3} nanosheets have abundant active sites for charge storage, and nitrogen-doped reduced graphene oxide intertwined with V_{2}O_{3} provide a flexible support. This indicates that the V_{2}O_{3}/N-rGO electrodes have abundant active sites, good mechanical integrity, and flexibility, resulting in high ion diffusion and electron transfer, and high capacity and high rate capability. The flexible V_{2}O_{3}/N-rGO film electrodes exhibit a high areal capacitance of 216 mF cm^2 at a current density of 1 mA cm^2. The all-solid-state flexible SCs fabricated by sandwiching two self-supported V_{2}O_{3}/N-rGO film electrodes with a PVA/LiCl gel electrolyte deliver an ideal volumetric capacitance of 8.1 F cm^3, an energy density of 0.55 mWh cm^3, and a power density of 0.035 W h cm^3. Moreover, the flexible all-solid-state devices have excellent cycling stability with 81% of the initial capacitance retention after 10 000 cycles. Hence, the flexible all-solid-state devices have promising potential in portable/wearable electronics due to their environmentally friendliness, good flexibility, and facile connectivity in series and parallel.

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Notes and references

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