

CARBON BASED SUPERCAPACITORS FOR EFFICIENT ENERGY STORAGE

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ABSTRACT

The development of contemporary electronic gadgets is heavily reliant on the availability of energy sources that are both extremely efficient and exhibit power density and energy density that are both high. The use of supercapacitors has a great deal of promise in this regard. Carbon nanomaterials, in particular carbon nanotubes, graphene, mesoporous carbon, and their hybrids, have been extensively researched as potential electrode materials for use in supercapacitors. This is primarily due to the singular hierarchical structure, exceptional electrical and mechanical properties, and high specific surface area that these materials possess. Specifically, the design and manufacturing of electrode structures, as well as the explanation of charge-storage mechanisms, are the primary focuses of this review paper, which provides a summary of the progress that has been made in high-performance supercapacitors that are based on carbon nanomaterials. Recent advancements in carbonbased supercapacitors that are flexible and stretchy are also described. These supercapacitors have the potential to be used in a variety of applications, such as integrated energy sources, self-powered sensors, and wearable electronics technology.

Keywords: Significance, energy storage, Carbon

INTRODUCTION

Sustainable energy solutions are becoming more necessary as a result of the increasing demand of energy, the excessive use of fossil fuels, and the deterioration of the physical environment. Solar, wind, and tidal energy are examples of renewable energy sources that have garnered a lot of interest; yet, the production cost, efficiency, and intermittent supply of these sources continue to be obstacles that prevent their broad acceptance. In addition, the availability of renewable energy sources like solar and wind is restricted during the nighttime or on days that are gloomy and windless. Because of these obstacles, the use of effective energy storage has become an essential component in the pursuit of sustainable energy, particularly when it comes to the incorporation of renewable energy sources. The



technologies of electrochemical energy generation (batteries) and storage (supercapacitors) have experienced exponential expansion in the recent past. These technologies have shown to be promising technologies that may be used to a wide range of application areas, including small-scale portable devices and automobiles. It is yet disappointing that these technologies are being used for energy storage on a significant scale in commercial applications, despite the fact that the energy storage system appears to be ideal for integrating with renewable energy sources.

In the present day, the most common types of devices used for energy storage are batteries and supercapacitors. Battery technology has brought about a revolution in the field of energy storage because of the great energy density that batteries possess, which is something that supercapacitors do not possess. Although they have a high power density, supercapacitors are excellent options for quick power delivery and recharging because of their high power density. It is necessary to make constant improvements in terms of the cycle efficiency, rate performance, cost, and safety of supercapacitors and batteries, despite the fact that these technologies are continuously undergoing development. Converting energy into chemical energy and storing it in the form of hydrogen, which is created by electrochemically splitting water, is another crucial requirement for capturing renewable energy. This transformative process may be accomplished by converting energy into chemical energy. Devices such as fuel cells are able to make use of this energy when certain conditions are met. Therefore, recent developments in energy storage and electrocatalytic hydrogen evolution reaction (HER) are of utmost significance in tackling the most pressing problems facing contemporary civilization. These problems include climate change as a result of the greenhouse effect and the depletion of fossil resources.

It is essential that the chemistry of the materials used for electrodes and electrocatalysts be taken into consideration when designing energy storage and conversion systems that make use of supercapacitors, batteries, and HER. The capacity of these materials to store electrical energy in the form of chemical energy is determined by the chemical bonds that they possess by themselves. A number of parameters, including as the electrochemical activity, conductivity, and structural stability of materials, are responsible for controlling the efficiency of charge storage and conversion. In a general sense, the efficiency of the system in terms of energy storage and conversion is directly proportional to the superiority of the electrochemical characteristics of the material. Accordingly, the design and development of materials that are specifically designed to fulfill the requirements of certain energy storage



applications has become an essential component of research in the field of materials science. An excellent illustration of the influence that improved material design has on the performance of energy storage is provided by the fact that the commercialization of lithiumion batteries was made possible by the discovery of LiCoO2/graphite and LiFePO4, which serves as a representative example. In order to fulfil the role of electrodes in energy storage systems, several kinds of materials have been created throughout the course of time. Nevertheless, the problematic concerns that need to be addressed on a continuous basis are the constraints that are characterized by poor energy density, low power density, and/or low durability. Specifically, batteries that have an anode layer made of inorganic materials exhibit a tendency to catch fire when subjected to high cyclability and load. Carbon-based nanostructures have evolved as leading materials in energy storage and conversion technologies, large surface area, and strong thermal and chemical stabilities. In this context, carbon-based nanostructures have emerged as leading materials.

Carbon-Based Nanomaterials

Carbon is one of the most significant and plentiful elements that may be found in the crust of the planet. Carbon may exist in a variety of allotropes, including graphite, diamond, fullerenes, nanotubes, and the wonder material graphene, which is composed of mono- or few-layered slices of graphite. In recent years, graphene has been the subject of much investigation. The arrangement of the carbon atoms strongly influences the physicochemical features of these allotropes, which are distinct from those of other allotropes. Before the discovery of fullerenes in 1985 by Richard E. Smalley, who was awarded the Nobel Prize in 1996, it was thought that graphite and diamond were the only stable forms of carbon. Fullerenes were one of the first stable forms of carbon. There is a widespread utilization of fullerenes as electron acceptors in solar cells due to their ability to operate as an electron-transferring medium with mobility ranging from 10-4 to 10-3 cm2 V-1 s-1. Fullerenes are materials that are low in electrons. Fullerenes have also been utilized extensively in the delivery of drugs, the production of supercapacitors, the storage of hydrogen, the production of fuel cells, and the application of an antibacterial layer on water pipes and lubricants.

Ijima made the initial observation of one-dimensional carbon nanotubes (CNTs) that included multiple walls later in the year 1991. It was initially discovered that carbon nanotubes (CNTs) were a component of fullerenes, also known as buckytubes or cylindrical fullerenes. Ijima announced the invention of carbon nanotubes (CNTs) by the use of an arc-discharge



evaporation technique not long after the observation was made. The study and development of carbon nanotubes (CNTs) was greatly sped up as a result of the subsequent synthesis of single-walled carbon nanotubes (SWCNTs) on substrates by the use of chemical vapor deposition (CVD) with the transition metals serving as catalysts on a variety of substrates, including SiO2, Al2O3, and ZrO2. In addition to their chirality-dependent metallic and semiconductor nature, excellent chemical and mechanical stability, and higher thermal and electrical conductivity, carbon nanotubes (CNTs) possess a multitude of fascinating properties and characteristics. These characteristics make them suitable for a wide range of applications, including but not limited to transistors, sensors, optical devices, energy storage devices, bio-applications, and many others.

Following the discovery of two-dimensional graphene that was exfoliated using Scottish tape by Andre Geim and Konstantin Novoselov in 2004, the study on carbon-based materials has been seeing a surge in popularity. Both of these individuals were awarded the Nobel Prize in 2010. This finding also kickstarts the investigation of a variety of two-dimensional materials. Because of its exceptional mechanical, thermal, electrical, and electronic characteristics, graphene is thermodynamically stable. Graphene also possesses amazing properties. Graphene has electron mobility on the order of 104 cm2 V-1 s-1 when subjected to atmospheric conditions. This material has the potential to be utilized in a variety of applications, including energy storage and conversion, sensors, and water-splitting. However, due to its zero band-gap nature, its applicability specifically in electronics is restricted. Doping graphene sheets with hetero-atoms such as nitrogen, boron, sulfur, and phosphorous has been done in order to introduce bandgap. This has been done in order to make graphene sheets suitable for use in field-effect transistors and energy storage devices.



Figure 1 A) Quantum chemical simulation of graphene flake-fullerene synthesis. TEM pictures of each structure are displayed in (B). Reprinted with permission. Springer Nature 2010, copyright. C) The schematic of graphene-to-CNT conversion using AuNPs as catalytic components at low temperatures without carbon sources. TEM pictures of AuNPs on graphene sheets before and after radio frequency CVD. Reprinted with permission. ACS copyright 2012.

OBJECTIVE

- 1. To conduct a cost and life-cycle study of the suggested supercapacitors for the applications they are intended for.
- 2. To create a variety of carbon-based materials and structures for use as electrodes in supercapacitors, and to use them in conjunction with a variety of electrolytes

Mesoporous carbon in EDLCs

When it comes to energy storage devices, activated carbon has been utilized extensively as electrodes due to the fact that it is simple to synthesize, inexpensive, and possesses an adequate electrical conductivity. Nevertheless, these benefits are hampered by the fact that it has a low effective specific surface area. This is because it contains micropores that are randomly linked and have a size of less than 2 nm. Electrolyte ions have a difficult time



communicating with these micropores. A supercapacitor electrode with a high specific surface area, a rapid ion-transport channel, and a high power density was investigated using mesoporous carbon with a bigger pore diameter ranging from 2 to 50 nanometers. This was done in order to address the problem it was causing. As an illustration, mesoporous carbon that was produced by carbonizing a combination of poly(vinyl alcohol) and inorganic salts had a specific capacitance of 180 F/g when it was placed in an electrolyte consisting of aqueous H2SO4. The volumetric specific capacitance, energy density, and power density of mesoporous carbon electrodes, on the other hand, might be directly controlled by the size and composition of the mesoporous material. For effective electrochemical energy storage, it is preferable to have a population of mesopores and micropores that is in equilibrium with one another. The size and geometry of the pores in mesoporous carbon may be well controlled by the use of a variety of synthetic processes, as was established in the previous section. When mesoporous carbon is manufactured as an ordered mesoporous carbon (OMC) with pores that are uniformly distributed and of a regular size, it has the capacity to assist charge storage and movement. As a result, the capacitance and rate capability of the material may be increased. High-performance organic matter composites (OMCs) with pore diameters of 2.8 nm (C-1) and 8 nm (C2) have been manufactured by utilizing SBA-16 silica with mesostructured templates and polyfurfuryl alcohol as the carbon source that was used. In a variety of electrolytes, the OMCs that were produced, both C-1 and C-2, which had a specific surface area of 1880 and 1510 m2/g, respectively, were put through their paces as supercapacitor electrodes. It was clear that the C-1 with a pore diameter of 2.8 nm had the largest specific capacitance, which reached up to 205 F/g. On the other hand, the C-2 with a pore diameter of 8 nm demonstrated superior stability when raising the rate. There is also the possibility of activation being done on mesoporous carbons in order to introduce micropores.

Xia et al., for example, activated mesoporous carbon with carbon dioxide at a temperature of 950 degrees Celsius. This process resulted in the introduction of micropores into the mesoporous carbon, which resulted in an increase in specific capacitance from 115 F/g in 6 M KOH to 223 F/g. There is a possibility that the creation of hierarchical pores with a high specific surface area (2749 m2/g) and the well-balanced populations of micropores and mesopores are responsible for the observed increase in specific capacitance. In recent years, there has been a growing interest in the creation of mesoporous carbon by the carbonization of non-traditional sources such as biomass. As an illustration, N-doped mesoporous carbon has been manufactured using the use of a one-step procedure that involves pyrolyzing the



mixture of milk powder and potassium hydroxide without the utilization of any mold. In terms of specific surface area, the N-doped mesoporous carbon (NMPC) exhibited a value of 2145.5 m2/g, while its pore volume was measured at 1.25 cm3/g. The NMPC presented a specific capacitance of 396.5 F/g at 0.2 A/g in 6 M H2SO4 when used as a supercapacitor electrode material. Additionally, it demonstrated a steady capacitance retention of 95.9% after 2000 cycles at 50 mV/s. The N dopant was present at a concentration of 2.5%. In addition, the geometry and structure of pores in mesoporous carbon have been investigated in order to enhance the electrochemical performance of the material.

Hybrid carbon nanomaterials in EDLCs

Carbon nanomaterials that have different structures can be mixed in order to display synergistic effects for the purpose of improving electrochemical performance. A high specific capacitance of 175 F/g was achieved by using carbon black to split graphene sheets in order to construct three-dimensional hybrid materials with little aggregation of graphene. This was accomplished by scanning the graphene sheets at a rate of 10 mV/s in an electrolyte containing 6 M potassium hydroxide. Mesoporous carbon spheres were sandwiched between graphene sheets in another piece of research, and the three-dimensional structure that was produced as a result had a specific capacitance of 171 F/g when scanned at the same 10 mV/s rate in 6 M potassium hydroxide. Particularly intriguing is the fact that carbon nanotubes (CNTs) were intercalated between graphene sheets in order to minimize the aggregation of graphene and so preserve its particular surface area. By enhancing the electrical conductivity and mechanical strength, the π - π interaction between graphene and carbon nanotubes (CNTs) can also be beneficial. Graphene has been utilized to make composites with oxidized carbon nanotubes (CNTs), just as GO is used to disperse carbon nanotubes (CNTs) in solvents. In this regard, Yu and Dai constructed hybrid films consisting of carbon nanotubes (CNT) and graphene that were linked with a well-defined nanoporous network. These films had a specific capacitance of 120 F/g in an electrolyte containing 1 M H2SO4 and a nearly rectangular cyclic voltammogram even when the scan rate was decreased to 1 V/s. Another noteworthy piece of research was published by Sun et al., in which graphene sheets were intercalated between carbon nanotubes (CNTs) in aligned carbon nanotube fiber. In spite of the fact that the hybrid fiber that was produced had a specific capacitance of just 31.5 F/g, it was significantly greater than the specific capacitance of the pure CNT fiber, which was 5.83 F/g. A continuous carbon nanotube (CNT) and graphene hybrid fiber with well-defined mesoporous structures was created by Yu et al. by the utilization of a modified hydrothermal



microreactor. This fiber exhibited a specific surface area of up to 396 m2/g and an electrical conductivity of 102 S/cm with a specific surface area. The volumetric specific capacitance of the matching fiber-shaped supercapacitor was measured to be 305 F/cm3 at a current density of 26.7 mA/cm3. Additionally, the volumetric energy density of the supercapacitor was measured to be 6.3 mWh/cm3, which is equivalent to the energy density of a thin-film lithium-ion battery with a capacity of 0.5 mAh and varying voltage. Additionally, a threedimensional N-doped carbon nanotube (CNT)/graphene network was produced by means of hydrothermal treatment and freeze-drying. This was followed by the carbonization of graphene oxide (GO) and the unadulterated carbon nanotube mixture in the presence of pyrrole. The hybrid carbon fiber that was produced had excellent electrochemical performance, particularly a capacitance retention of 96% after 3000 cycles on the experiment. In the example of self-assembled carbon-composite material, the specific capacitance of the freestanding 3D graphene hydrogel and carbon nanofiber composite material was measured to be 150.2 F/g at a current of 1 A/g. Furthermore, the material retained 97.8% of its capacitance performance after undergoing 2000 cycles. Additionally, a network of nanotubes and carbon nanofibers was created from conjugated polymer with the purpose of creating electrochemical energy storage. The following table provides a summary of electrical doublelayer supercapacitors (EDLCs) that are based on carbon.

Carbon-based stretchable and twistable supercapacitors (film-/fiber-shaped)

Stretchable and twistable FSCs are required for advanced electronics, such as polymer-based self-powered sensors, polymer light-emitting diodes, polymer solar cells, and active matrix displays, to mention a few. These FSCs are required in addition to the FSCs that have been discussed above. In addition to these early publications on stretchable SCs, buckling SWNT/polydimethylsiloxane (PDMS) electrodes have garnered a significant amount of attention due to the fact that they are able to demonstrate a strain of up to 140% without exhibiting any change in resistance. In order to fabricate flexible and high-performance electrodes for SCs, the utilization of crumpled graphene sheets resulted in a reduction in both the cost and the complexity of the process. With a high specific capacitance of 196 F/g in H3PO4-PVA electrolyte, the crumpled graphene-paper-based electrode displayed strong stretchability up to 300% linear strain and 800% aerial strain. Additionally, it demonstrated dependability up to 1000 stretch/relax cycles. In addition, Kim et al. have reported a delamination-free stretchable supercapacitor, in which all the component layers were prepared with a single matrix composed of an ionic liquid, 1-ethyl-3- methylimidazolium



bis(trifluoromethylsulfonyl)imide. and a polymer, poly(vinylidene fluoridehexafluoropropylene), as an electrolyte and a supporting layer, respectively, in the stretchable supercapacitor. In order to construct the electrode layer, carbon nanotubes (CNTs) were included into the common matrix, which was made of polymer. All of the layers were then smoothly bonded into one body by dissolving the surface of the composite with acetone. As a result of the utilization of ionic liquid-based gel electrolytes, the operating cell voltage reached a maximum of three volts. Both the specific electrode capacitance and the areal cell capacitance were measured to be 67.2 F/g and 12.7 F/cm2, respectively. After undergoing 500 cycles of lateral and radial strains at a strain of 0.5, the capacitance exhibited just $\pm 2.1\%$ and $\pm 1.4\%$, respectively, as the standard deviations. Polypyrrole (PPy)-coated manganese dioxide nanoparticles were placed onto carbon nanotube (CNT)-based textile supercapacitor electrodes. This resulted in an increase of 38% in the electrochemical energy storage capacity of MnO2/CNT-based flexible (13% bend) and stretchy (21% tensile strain) supercapacitors. A specific capacitance of 461 F/g was recorded in an electrolyte composed of H3PO4 and PVA at a current density of 0.2 A/g. This particular capacitance was attributed to the inhibition of delamination of MnO2 nanoparticles thanks to the application of PPy coating. In addition, the capacitance retention was 96.2% even after 750 000 cycles of bending, which is equivalent to 13% of the total. stretchy micro-supercapacitors (MSC) have been manufactured with the use of electrode materials and stretchy substrate supports that consist of a honeycomb PDMS structure and a thin coating of supercritical carbon nanotubes (or SWNT). The greatest strain in the MSC areas seen in an array of 4×4 MSCs was found to be over 5 orders of magnitude lower than the strain that was applied, which was around 150 percent. Furthermore, the capacity of the device remained unchanged even when stretched to a stretch of 150%.





Figure 2 The fiber synthesis process involves injecting a homogeneous solution of acid oxidized SWNTs, GO, and EDA into a flexible silica capillary column, followed by in-situ thermal treatment at 220°C for 6 h. A continuous fiber is then pushed into a water reservoir using pressurized nitrogen flow. Photograph of water-collected as-prepared fibers. (c) Dry fiber with ~50 mm diameter and ~0.5 m length (~20 inches). Bending fibers creates planes. Fiber spring compression and stretch. A fiber-knitted cloth. All scale bars: 0.5 cm. (g) Schematic of a PET-based micro-SC with two fiber-3 electrodes. (h) 1000-cycle capacitance retention at 908 bending angle. Photo of bent micro-SC. (i) Micro-SC-powered TiO2 nanorod array UV photodetector current response assembly. Reprinted with permission from Macmillan Publishers Ltd (2014).

Carbon-based ultrafast supercapacitors for ac-line filtering



Alternating current (ac) line filtering, which is accomplished by the utilization of ultrafast supercapacitors, is a crucial component for the utilization of domestic electricity in order to eliminate undesirable high-frequency disturbances. The frequency of alternating current (ac) electricity can be either 50 or 60 hertz. Most of the time, higher-order harmonics (over 120 Hz) of the fundamental generating frequency are induced when a number of distinct nonlinear loads from a variety of electronic equipment in residential necessities, portable electronics, autos, and medical appliances are combined. ac-line filtering is accomplished with the help of aluminum electrolyte capacitors (AECs), which are utilized for the purpose of shielding electronic equipment from voltage ripples. AECs, on the other hand, have a low specific capacitance, and as a result, they take up a significant amount of space and volume in electronic circuits.

Taking this into consideration, supercapacitors, which have a specific capacitance that is two to five orders of magnitude larger than that of AECs, have the potential to be utilized for efficient ac-line filtering while occupying a very small amount of space or volume in capacitive components. When a supercapacitor is inserted into transmission lines, it typically behaves in a manner similar to that of a resistor at a frequency of 120 Hz. As a result of the high electrochemical series resistance and microporous structure of supercapacitor electrodes, the typical resistor-capacitor (RC) time constant for a supercapacitor is approximately one second. This time constant is far too long to be useful for the common application of 120-Hz filtering, which has a period of approximately 8.3 milliseconds. This indicates the need to smooth out the residual alternating current ripples in most line-powered electronics. Specifically, this is due to the fact that supercapacitor electrodes with inadequate pore shapes either hinder high-rate ion diffusions or inhibit effective charge transfer due to their high resistances. Consequently, the efficiency of ac-line filtering may be improved by the design and manufacture of highly conductive electrodes that have micro- and nano-architectures that have been tuned for the most efficient transit of electrons and ions. Therefore, materials having a large surface area and a lower percent of intrinsic porosity have been investigated for use in such applications. Because of their superior electrical conductivity and high specific surface area, graphene-based materials and graphene/CNT hybrid structures have recently emerged as promising alternatives to conventional carbon materials. These materials are utilized to improve related rate capability for ac-line filtering. Other electrode materials that are utilized include onion-like carbon and carbon nanotubes (CNTs), carbide-derived carbon, metal oxides, polymers, and mesoporous carbons. It has also been established that



graphene and porous carbon composites are good ac-line filters; nevertheless, there is still room for improvement in terms of their energy-storage capacities.



Figure 3 (a) SEM pictures of 50% omnidirectional prestrained CNT film buckling structures. (b) Digital photos of buckled CNT film stretching. CNT/PANI SC scan rate-specific capacitance fluctuation. Reproduced with permission from American Chemical Society (2016). (d) Solid-state coiled supercapacitor schematic with two symmetric MnO2/CNT core-shell-coiled electrodes and gel electrolyte. Stress loading/unloading graphs of the hybrid MnO2/CNT coiled electrode with 20%–40% tensile stresses. Reprinted with Wiley (2016) permission.

In a recent study, Lim et al. revealed that the substitutional pyridinic nitrogen dopant sites in carbon nanotubes had the ability to selectively trigger the unzipping of CNT side walls at a very low electrochemical potential (0.6 V). In the end, the nanostructures that were produced were composed of graphene nanoribbons that were either partially zipped or unzipped and wrapped around carbon nanotube cores. These nanostructures were able to preserve the two-dimensional crystallinity while exhibiting a clearly defined atomic arrangement at the unzipped borders. The performance of the ultrahigh-power supercapacitor was achieved through a synergistic interaction between the large surface area and the robust electrical connectivity of the unique nanoarchitecture. This resulted in the supercapacitor being able to serve as an ac filter with a record high-rate capability of 85° (which is very close to the phase angle capability of AECs, which is 83.9°) at 120 Hz. On nickel electrodes, Lin et al. also created a micro-supercapacitor that was based on a three-dimensional graphene/carbon nanotube carpet (G/CNTC). The G/CNTC displayed a phase angle of 81.5° while operating at



a frequency of 120-Hz. In spite of this, a significant amount of work has to be done in order to produce supercapacitors that are capable of filtering alternating current lines and storing an exceptional amount of charge for use in different practical applications.

CONCLUSION

Carbon nanomaterials, such as one-dimensional carbon nanotubes (CNTs), two-dimensional graphene, three-dimensional mesoporous carbon, and their composites with conductive polymers or metal oxides, have been utilized extensively as electrodes in supercapacitors, including EDLCs, PCs, and home solar cells (HSCs). In general, pure carbon nanomaterials that do not contain any functional groups are advantageous for use as EDLC electrodes due to the fact that they have a large specific surface area and great electrical conductivity. One of the advantages of EDLC is its high-rate capability, which it possesses, as well as its exceptional cyclic stability, which includes the retention of 95% to 100% after 1000 to 10,000 cycles. It has been established that the specific capacitance of pure carbon nanomaterials in EDLC falls somewhere in the region of 10–300 F/g. There is a possibility of increasing the specific capacitance of carbon-composite nanomaterials by one order of magnitude, which is typically between 100 and 1000 F/g. Therefore, the energy density may be significantly enhanced by combining carbon nanomaterials with other materials that possess pseudo-capacitances, such as conducting polymers, metal oxides, or hydroxyls. However, after 1000 cycles, their rate capacity and cyclic stability may decline to sixty to ninety percent. There have been a great number of recent attempts made to enhance the electrochemical performance of supercapacitors that are based on carbon nanomaterials. These efforts have been conducted in order to increase the specific capacitance, energy density, power density, rate capability, and/or cyclic stability of these supercapacitors. Approaches that have been shown to be effective in producing high-performance carbonbased SCs include the design and development of innovative three-dimensional electrode architectures, as well as the compositing of carbon nanomaterials with other active materials. Through the enhancement of energy and power density inside a single electrochemical device, hybrid supercapacitors have the potential to bridge the gap that exists between a supercapacitor and a battery at the same time.

REFERENCES

 Dai L, Chang DW and Baek JB et al. Carbon nanomaterials for advanced energy conversion and storage. Small 2012; 8: 1130–66.



- 2. Yang Z, Ren J and Zhang Z et al. Recent advancement of nanostructured carbon for energy applications. Chem Rev 2015; 115: 5159–223.
- 3. Zhu J, Yang D and Yin Z et al. Graphene and graphene-based materials for energy storage applications. Small 2014; 10: 3480–98.
- Cao X, Yin Z and Zhang H. Three-dimensional graphene materials: preparation, structures and application in supercapacitors. Energy Environ Sci 2014; 7: 1850– 65.
- 5. Huang X, Tan C and Yin Z et al. 25th anniversary article: hybrid nanostructures based on two-dimensional nanomaterials. Adv Mater 2014; 26: 2185–204.
- 6. Tan C and Zhang H. Two-dimensional transition metal dichalcogenide nanosheetbased composites. Chem Soc Rev 2015; 44: 2713–31.
- 7. Huang X, Zeng Z and Zhang H. Metal dichalcogenide nanosheets: preparation, properties and applications. Chem Soc Rev 2013; 42: 1934–46.
- Miller JR and Simon P. Materials science: electrochemical capacitors for energy management. Science 2008; 321: 651–2.
- 9. Odom TW, Huang JL and Kim P et al. Atomic structure and electronic properties of single-walled carbon nanotubes. Nature 1998; 391: 62–4.
- 10. Cherusseri J, Sharma R and Kar KK. Helically coiled carbon nanotube electrodes for flexible supercapacitors. Carbon 2016; 105: 113–25.
- 11. Graham AP, Duesberg GS and Hoenlein W et al. How do carbon nanotubes fit into the semiconductor roadmap? Appl Phys A 2005; 80: 1141–51.
- Yu MF, Files BS and Arepalli S et al. Tensile loading of ropes of single wall carbon nanotubes and their mechanical properties. Phys Rev Lett 2000; 84: 5552–5.