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High-capacity pseudocapacitive Li storage on functional nanoporous carbons with parallel mesopores

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Abstract

Pseudocapacitive storage of monovalent alkali cations, such as Li\textsuperscript{+} and Na\textsuperscript{+}, is critically important for the development of metal-ion capacitors. Functional carbon materials decorated with ketone-containing groups are excellent candidates for this purpose. An epoxidation approach was deployed in this work to decorate electroactive oxygen groups on a high surface area nanoporous carbon with aligned mesopores. Because of the turbostratic structure, the intermediate epoxides dissipated into double-bonded oxygen groups in the functionalized carbon. The synergy of large porosity, good conductivity and enhanced surface redox activity endows the functionalized carbon cathode with high capacity (313 mA h/g@50 mA/g), good stability (>200 cycles) and high rate capability (148 mA h/g@400 mA/g).

Keywords: lithium-ion capacitors, oxygen functional groups, nanoporous carbons

1. Introduction

Deployment of alternative renewable energy resources, including solar, wind, or tide, is becoming global consensus for secure sustainability of modern
Nevertheless the typical non-fossil renewable energy is intermittent and non-dispatchable. Full spectrum utilization of renewable energy for either stationary, portable or remote conditions will thus rely on the dispatchable energy storage devices.

At present the most popular energy storage devices are batteries and supercapacitors because of the high efficiency and reliability. Batteries have high energy density while supercapacitors provide large power output. For instance commercial lithium ion batteries possess a specific energy upwards to 200 Wh/kg but with a maximum specific power of 300~400 W/kg. On the contrary, supercapacitors can deliver a very high specific power of 10 kW/kg but with a specific energy of only about 5~20 Wh/kg. It would be ideal to realize a hybrid energy storage device that stores both high power and high energy.

Metal-ion capacitors, including Li-ion capacitors and Na-ion capacitors, are a family of hybrid energy storage system [1, 2]. The normal Li/Na-ion capacitors use an intercalation-type negative electrode (anode) and an electric double layer-type positive electrode (cathode). Various materials have been paired for this purpose, for instance V$_2$O$_5$/carbon nanotubes(−)//activated carbon(+) [1], Li$_i$Ti$_5$O$_{12}$(−)//graphene(+) [2], nanotubular TiO$_2$(−)//mesoporous carbon(+) [3], TiO$_2$(B)(−)//activated carbon(+) [4]. All-carbon Li/Na-ion capacitors are a relatively new concept, where the graphitic materials, including graphene and biomass carbons, are used for the anode intercalation storage [5, 6]. However, the energy density of metal-ion capacitors is limited by the low cathode capacity due to the absence of Faradaic reactions.

The electroactive oxygen groups on conjugated network can reversibly react with monovalent cations (H$^+$, Li$^+$, Na$^+$, etc.) via fast surface redox reactions [7-13]. Carbon materials are conjugated and contain a variety of oxygen groups on the surfaces, edges and defects. This physicochemical nature obviously endows carbon materials with intrinsic electrochemical redox activities. This
understanding inspired the use of functional carbons as a new generation cathode in Li/Na-ion capacitors as long as the reaction potentials are reasonably higher than the counter anode reactions. Recently a range of carbon materials (graphene, carbon nanotubes, etc.) rich in oxygen functional groups have been tested as cathodes with high capacity, long-term stability and good rate performance for Li/Na-ion storage [14-23]. Alternatively Li-storage cathodes can be achieved via surface decorations of carbons with quinone-containing electroactive polymers [24, 25]. Most of these studies are on graphitic nanocarbons, like graphene or carbon nanotubes. Graphitic nanocarbons are extremely popular in regards of macroscopic assembly and flexible device. Nevertheless nanoporous carbons with high surface area, good conductivity and tunable texture are important traditional carbon materials in energy storage. The functionalization of nanoporous carbons with periodic textures for pseudocapacitive Li-storage may bring more interest back to this ‘old’ branch of carbon materials towards emerging technologies.

Herein, we report the use of epoxidation to functionalize nanoporous carbons (NPC) with aligned mesopores to improve the lithium storage capacity. Our previous study showed the reversible lithium storage by epoxides on the basal plane of graphene oxide [20]. It was reported that epoxidation of graphite produced graphite epoxide [26]. As the conductivity of graphene oxide is low, the original aim of this work was hence to functionalize conducting porous carbons through epoxidation with the purpose of comprehensively utilizing the electroactive epoxide groups on a relatively conducting matrix. Compared with the pristine NPC, the oxidized NPC (oNPC) contains more oxygen due to epoxidation. However ketone-containing groups represent the majority oxygen in oNPC. This result was surprising but reasonable as the carbon structure of NPC is turbostratic rather than graphitic. Nevertheless our electrochemical tests showed the enhanced lithium storage capacity in the oNPC cathodes. The cathodes made of oNPC showed a maximum capacity up to 313 mA h/g at 50
mA/g in comparison with 195 mA h/g for NPC. A stable capacity around 225 mA h/g is achievable for 160 cycles at 100 mA/g. Despite the partially collapsed nanoporous texture caused by epoxidation, the oNPC exhibited a capacity of 148 mA h/g at 400 mA/g, whereas the capacity of NPC was only 95 mA h/g at the same current density.

2. Experimental

2.1 Synthesis and epoxidation of nanoporous carbons

The pristine nanoporous carbon sample was synthesised by a templating approach for which an ordered mesoporous silica (SBA-15) was used as a template [27]. The NPC sample was synthesized by filling the nanochannels with sucrose as the carbon precursor. The sucrose-filled silica was carbonized in argon atmosphere. The resultant silica/carbon composites were washed with NaOH dissolved in a deionized water/ethanol (volume ratio 1:1) (0.1 M) solution at 90 °C for 3 h to remove the silica template. The remaining carbon was then filtered and rinsed until the pH was 7. Thereafter, the wet powder was dried under vacuum at 100 °C for 12 h and denoted as NPC.

The epoxidation of NPC was conducted by dispersing NPC in a dichloromethane solution of 3-chloroperbenzoic acid and stirred for 5 days at room temperature. The solid product was collected by filtration and washed by using dichloromethane. The final product was dried in vacuum at 100 °C for 12 h and denoted as oNPC.

2.2 Materials characterization

Transmission electron microscopy (TEM) was collected by using JEOL 1010 at an accelerating voltage of 100 kV. X-ray photoelectron spectroscopy (XPS) was measured on a Kratos Axis Ultra spectrometer using Al Kα radiation (15 kV, 150 W). The survey spectra were recorded from 0 to 1000 eV at an energy interval of 1 eV/step. Thermal gravimetric analysis (TGA) was carried out on a TGA Metter Toledo analyzer under nitrogen protection at a heating rate of 5 °C
min\(^{-1}\) from 25 to 800 °C. Porosity measurement was conducted on a Micromeritics Tristar II at 77 K. The Raman spectra were collected with a Renishaw Raman microscope by using 514 nm Ar laser. Fourier transform infrared (FTIR) spectroscopy was performed on the PerkinElmer Spectrum 400 Spectrometer with a sensitive liquid nitrogen-cooled MCT detector.

2.3 Electrode preparation and characterisation

Both of the NPC and oNPC samples (80 wt%) were ground and homogeneously mixed with conductive carbon black (10 wt%) and polyvinylidene fluoride (PVDF) (10 wt%) in N-methyl-2-pyrrolidone to form a slurry. The slurry was stirred for 6 h and coated onto Al foil. After vacuum-drying at 120 °C overnight, the foil was punched into circular pieces with a diameter of 15 mm, which was used as the cathodes. The electrolyte was 1 M LiTFSI salt in 1,3-dioxolane (DOL) and 1,2-dimethoxyethane (DME) (1:1 vol). The cathodes were assembled into 2032 coin cells in an argon-filled glove box (MBraun UniLab) with a lithium chip as an anode and a polypropylene film as a separator.

The galvanostatic charge–discharge tests were conducted on a LAND battery test system. The voltage window is 1.0-4.0 V vs. Li\(^+\)/Li\(^0\). The cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) measurements were measured on a Biologic VMP-3 electrochemical workstation. EIS measurements were conducted at the frequency range from 100 kHz to 10 mHz.

3. Results and discussion

The XPS survey spectra of the oNPC and NPC are shown in Figure 1a. The pristine NPC sample contains mainly carbon and oxygen with a trivial signal from nitrogen. The atomic percentages of oxygen and carbon in the pristine NPC are 7.5 at.% and 92.5 at.%, respectively. The NPC was synthesized through carbonizing dehydrated sucrose loaded in mesoporous silica template.
The dehydrated sucrose contains considerable amount of hydroxyl groups, part of which would remain in the final sample after thermal treatment. This is the origin of the oxygen in NPC. The epoxidation of NPC was carried out in a dichloromethane solution by using 3-chloroperbenzoic acid as the oxidizing chemical. After epoxidation, the oxygen content increased to 19.1 at.%, which leaded to the reduction in carbon content to 79.3 at.%. Around 1.8 at.% chlorine was detected on the surfaces of oNPC which is from the residues of either dichloromethane or 3-chloroperbenzoic acid. Given the rather low concentration of chlorine, the effect of epoxidation on the physicochemical and electrochemical properties of oNPC is believed to originate from the newly born oxygen groups.

On account of the different sources for the oxygen in NPC and oNPC, it is interesting to differentiate their respective chemical components. The deconvoluted profiles of C1s spectra of NPC and oNPC are displayed in Figure 1b. The spectra were fitted by taking into account various possible chemical structures of carbon in our samples. The peak C-I at 284.8±0.2 eV is assigned to the sp² type carbon, while the C-II peak at 285.8±0.2 eV is allocated to the sp³ type carbon considering the fairly turbostratic structure of sucrose-derived carbons. The peaks of C-III (286.8±0.2 eV), C-IV (288.2±0.2 eV) and C-V (289.1±0.2 eV) are respectively correlated with singly bonded oxygen, carbonyl and carboxyl groups. The peak C-VI (291.1±0.2 eV) reflects carbon atoms forming the pi-pi* bond. The variation of percentage for individual chemical component of C1s is compared in Figure 1c. With the similar content of sp² carbon in both samples, the population of sp³ carbon drops from 12.88% of NPC to 6.52% of oNPC. This change may indicate that the epoxidation occurred on those less stable or more reactive sp³ carbon instead of the sp² carbon. Surprisingly, the epoxidation did not give rise to a higher portion of singly bonded oxygen (either epoxide or phenol/hydroxyl) in the oNPC sample, in comparison with the pristine NPC sample. It has been known that stable
Graphite epoxide was synthesized from epoxidation of graphite by using a similar approach [26]. However, since the C-C bonds are the more reactive sites relative to C=C in sucrose-derived carbon, those fresh epoxides could be preferentially anchored on dangling C-C bonds. As a result, these intermediate epoxides became less stable and transformed into other double-bond structures. This structural transformation is postulated because the total population of carbonyl and carboxyl groups in oNPC is 14.3% more than double of the 6.70% in NPC. As the epoxidation caused damage to the carbon structure, the content of pi-pi* bond decreased from 6.12% of NPC to 3.73% of oNPC. The existence of these oxygen functional groups is verified from the FTIR spectrum shown in Figure 1d. The 36.8 wt% weight loss of oNPC at 800 °C is related to the deoxygenation as determined by thermogravimetric analysis (Figure S1).
Figure 1. (a) the XPS survey profiles for NPC and oNPC, (b) the fitted high-resolution C1s profiles for NPC and oNPC, (c) the percentage of six types of chemical components in C1s for NPC and oNPC, and (d) FTIR spectrum for oNPC.

The change in the porous texture of oNPC is analyzed by using N\textsubscript{2} cryo-sorption technique. Figure 2a compares the adsorption-desorption isotherms for NPC and oNPC. The epoxidation has removed a high percentage of micropores and mesopores as illustrated by the loss of adsorption capacity at the low and medium relative pressures. The specific surface area calculated from BET model for NPC and oNPC is 1443.9 m\textsuperscript{2}/g and 523.7 m\textsuperscript{2}/g, respectively. The total pore volume of oNPC is 0.42 cm\textsuperscript{3}/g, about 1/3 of that of NPC (1.30 cm\textsuperscript{3}/g). The loss of porosity after epoxidation could be the result of the localized collapse in the mesoscale channels. The pore size distribution profiles for NPC and oNPC are displayed in Figure 2b. In the mesopore range, the NPC sample has a main distribution peak centered at 3.4 nm. This peak distribution remains in the oNPC sample, accompanied with a neighbor peak at
2.7 nm. This result indicates the formation of smaller mesopores after epoxidation. The origin could be either the collapse of larger mesopores or the merging of side-by-side micropores. In the micropore region, both peaks located at 1.3 and 1.5 nm remain. Our previous study showed the gradual loss of mesopores as the oxidation intensity increased when nitric acid was used to oxidize nanoporous carbons [28]. The effect of epoxidation on porosity development follows the same trend.
Figure 2. Porosity analysis results for pristine nanoporous carbon and oxidized nanoporous carbon: (a) Nitrogen adsorption-desorption isotherms and (b) Pore size distribution derived by non-linear DFT model. (c) Raman spectra for pristine and oxidized nanoporous carbons.
TEM was used to characterize the texture of the mesoscale channels before and after epoxidation. As shown in Figure 3a, the NPC particles are rod-like with length of about 300-500 nm and width of ~100 nm. The particle morphology of oNPC is shown in Figure 3c. As illustrated, the original shape is preserved accompanied with those tiny flakes on the surfaces that could be produced by epoxidation. The channels are roughened indicating the inner surfaces of the mesopores are also oxidized. Meanwhile some parts of the channels maintain the parallel orientation. The high-magnification TEM images shown in Figure 3b and d demonstrate the straight and parallel mesopores in a NPC rod whereas some collapsed areas are observed along the parallel mesopores in the oNPC rod. This observation agrees with the loss of mesopore volume derived from N\textsubscript{2} adsorption analysis.

Figure 3. TEM images for pristine nanoporous carbon (a, b) and oxidized nanoporous carbon (c, d).
Raman spectroscopy was used to evaluate the carbon structure change. The D-mode of oNPC is broader compared to that of NPC. The $I_D/I_G$ ratio for oNPC is 0.86, larger than that of NPC (0.75). This is because the oxidation of carbon gives rise to more defects, as indicated by the XPS analysis. The average distance between defects (LD) can be derived from an established relation in the form $I_D/I_G = 102/LD^2$ [29]. The LD values for oNPC and NPC are 10.89 and 11.66, respectively. The smaller LD value for oNPC indicates the evolution of more defects through epoxidation that minimized the distance in average between defective sites.

The electrochemical reactivity of the newly planted oxygen functional groups on oNPC is characterized in a lithium-containing electrolyte in the potential range of 1.0 to 4.0 V vs. Li$^0$/Li$^+$. The cyclic voltammetry (CV) profiles are shown in Figure 4a. Two pairs of redox peaks are noticed: A1/C1 and A2/C2. The cathodic peaks refer to the reduction of oxygen functional groups by Li$^+$, whereas the anodic peaks suggest the oxidation of lithiated oxygen functional groups [14]. The electrolyte reaction starts to take place when the electrode potential is either lower than 1.25 V or higher than 3.8 V. The electrolyte reaction may be related to the formation of solid electrolyte interphase on the material surfaces. To elucidate the formation of solid electrolyte interphase, we further adopted SEM and TEM analysis on the recovered discharged and charged samples. As shown in Figure S2, the surfaces and the cavities between the carbon nanorods are filled with smooth polymeric films which are the decomposition products of electrolyte at the low and high voltages.

The current at the anodic peak A1 (2.74 V) was found to increase linearly with scan rate as shown in Figure 4b, indicating a surface-redox limited process, which is in good agreement with the proposed mechanism of lithiation/delithiation of surface oxygen functional groups on oNPC. The stabilized galvanostatic charge-discharge profiles at 50 mA/g for NPC and oNPC are shown in Figure 4c. In comparison with the NPC electrode, the
oNPC electrode delivers a much larger capacity of 250 mA h/g. The charge accommodation on porous carbon electrodes can be simply divided into non-faradaic double layer capacity and faradic redox capacity. Since the double layer capacity is linearly related to the electrode potential, a straight dashed line is drawn in Figure 4c to represent the case of an ideal electric double layer cathode. Given the clean surface, i.e. heteroatom-free, the capacity of a carbon cathode at different potentials can be projected along this dashed line. In other words, the actual capacity of a virtual heterogeneous carbon electrode should deviate from this dashed line owing to the contribution of surface chemical groups to redox capacity. It is obvious that both NPC and oNPC electrodes possess certain amount of redox capacity. Bearing in mind of the oxygen-containing surface structure of NPC, it is reasonable to see the extra redox capacity. As the oxygen content increases, typically with the accumulation of extra ketone-containing groups after epoxidation, the deviation of oNPC from the dashed line is more significant. This finding is correlated with the lithium storage on the double-bonded oxygen functional groups, which is consistent with previous reports that carbonyl or carboxyl groups can participate in the surface lithiation or delithiation reactions [14]. The slope of charge-discharge profile starts to reduce when the potential is above 3.8 V or below 1.25 V, which is caused by the reactions with electrolyte in agreement of the CV results. It is noticed that these side reactions contribute to the total capacity.
Current (mA) vs. Voltage (V vs. Li$^0$/Li$^+$)

- A1: 2.74 V
- C1: 1.87 V
- A2: 3.65 V
- C2: 3.15 V

Scan rate: 0.1 mV/s, 0.2 mV/s, 0.4 mV/s

(b) Linear fit: R$^2$=0.9989
(c) [Graph showing voltage (V vs. Li⁰/Li⁺) vs. specific capacity (mA h/g) with different curves for NPC and oNPC. Key features include electrolyte reaction, C_{EDL}, + Li-epo capacity, and + Li capacity.]

(d) [Graph showing voltage (V vs. Li⁰/Li⁺) vs. specific capacity (mA h/g) with different current densities of 50 mA/g, 100 mA/g, and 400 mA/g. Key features include electrolyte reaction and specific capacity (mA h/g).]
Figure 4. (a) Cyclic voltammograms of the oNPC cathode scanned at 0.1, 0.2 and 0.4 mV/s, (b) the current at peak A1 (2.74V) versus scan rates, (c, d) the discharge-charge curves of the second cycle of NPC and oNPC cathodes at (c) 50 mA/g and (d) 100, 200, 400 mA/g. (e) The capacity and coulombic efficiency versus number of cycles at a range of current densities.

The charge-discharge curves of NPC and oNPC electrodes under different current density are compared in Figure 4d. With the current density increasing from 100 mA/g to 400 mA/g, the specific capacity of oNPC shifts from 209 mA h/g to 148 mA h/g. These values are comparable with the highest capacity (221 mA h/g@100 mA/g) of graphene-based cathodes in literature to the best of our knowledge [22]. In contrast, the specific capacity of NPC for the same range of current density changes from 130 mA h/g to 95 mA h/g. It is obvious that the capacity of oNPC cathode is higher than the capacity of NPC even when the oNPC is measured at a higher current density. The capacity retention ratio for oNPC and NPC in this range of current density is 70.8% and 73.1%.
On account of the partially collapsed mesoscale channels in oNPC, it is more or less surprising that the two samples have comparable capacity retention ratios. Figure 4e compares the rate performance and life of cycle for NPC and oNPC. Both cathodes were initially tested at 50, 100, 200 and 400 mA/g, each for 20 cycles and then tested at 100 mA/g for additional 160 cycles. The first cycle at 50 mA/g gives the highest capacity for either NPC or oNPC. The discharge capacity for the first cycle of 50 mA/g for NPC and oNPC is 195 and 313 mA h/g respectively. The discharge capacity in the second cycle drops to 162 and 251 mA h/g for NPC and oNPC respectively. The discharge capacity in the 2\textsuperscript{nd} cycle is about 17~20% less than that in the 1\textsuperscript{st} cycle. This is possibly related to the consumption of hydroxyl groups that cannot reversibly react with lithium and the irreversible decomposition of electrolyte that forms solid electrolyte interphase. As the cycling test continues, the coulombic efficiency stabilizes around 97~99\%, indicating that the reversible cathode reactions dominate after the beginning stage. Both the NPC and oNPC were found quite stable upon the cycling at 100 mA/g for 160 cycles, which indicate their potential for long-term charge-discharge as cathodes of lithium ion capacitors. Obviously the high capacity of oNPC makes it more advantageous to NPC.

Since the oNPC is derived from epoxidation, it could be interesting to compare the electroactivity of oNPC with graphene oxide which contains remarkable amount of oxygen that is mainly in the form of epoxide [20]. At the same current densities of 100 and 200 mA/g, it is found that oNPC has capacities of 209 and 179 mA h/g, which are comparable with the 219 and 161 mA h/g of graphene oxide. Nevertheless, the capacity retention ratio of graphene oxide at 200 mA/g referring to 100 mA/g is 73.5\%, much less than the 85.6\% of oNPC. This worse rate performance of graphene oxide is because of its insulating property. From this perspective, it is critically important to ensure good conductivity of the carbon matrix to enable effective utilization of the surface functional groups. On the other hand, it is noticeable that graphene oxide
possesses a much higher content of oxygen (31.0 at.%) than that of oNPC (19.1 at.%). This fact reflects that those oxygen groups on oNPC can provide more active charge storage sites than those on graphene oxide. There could be two reasons: 1) epoxide becomes unstable upon charge-discharge resulting in lower amount of oxygen participating in the cathode reaction; and 2) the poor conductivity of graphene oxide, typically the isolated sp² domains, restricts the efficient electron transfer to the electroactive epoxide areas on basal plane. However, it is still suggested more efforts could be devoted to understanding the roles of epoxides on graphitic carbons in electrochemical storage of monovalent cations, considering the unique physicochemical properties of epoxides and the difficulty in the synthesis of highly porous graphite epoxide [17, 20, 26].

![Graph showing CPS and binding energy](image-url)
Figure 5. (a) XPS survey profiles of three oNPC cathodes recovered from coin cells held at OCV, fully discharged and fully charged conditions, (b) the ratio of atomic percentage of lithium to carbon and oxygen on the recovered oNPC cathodes.

The roles of oxygen groups on oNPC in the capacity enhancement can be further elaborated by XPS surface analysis conducted on the electrodes under either charged or discharged status. The three conditions of electrodes being investigated are the open circuit voltage (OCV) condition, the fully discharged condition, and the fully charged condition. One electrode was held in a coin cell at OCV (~3V) for 12 hours before disassembly for XPS analysis. Another two electrodes were discharged to 1 V or recharged to 4 V respectively. These two electrodes were separately recovered from the corresponding coin cells for XPS analysis. The discharge and recharge were conducted at 50 mA/g. All electrodes were rinsed in DOL/DME solvent and dried in vacuum oven prior to the XPS measurement. The survey profiles shown in Figure 5a reveals the presence of fluorine and sulfur both of which are from the TFSI⁻ anions. As there is no sulfur but fluorine that is from PVDF in the OCV sample, it is
believed that all the TFSI\(^-\) anions were washed away from the OCV electrode. Note that lithium was only detected on the discharged or charged electrodes, not on the OCV electrode (inset of Figure 5b). The ratios of lithium to oxygen or carbon at the discharged status are higher than that at the recharged status. According to the cyclic voltammetry, the discharge process is related to the reduction of ketone groups by lithium where the lithium ions are bound with oxygen atoms. When the oNPC cathode is oxidized during recharge, the lithiated ketone groups release the lithium ions to the electrolyte. The XPS quantitative analysis is in agreement with the electrochemical measurement.

The epoxidation process and the lithium storage reactions are depicted in Figure 6. The structural characterization combining electron microscopy, surface spectroscopy and porosity analysis shows the thorough oxidation of the nanoporous carbons surfaces. As the epoxidation is preferential on the sp\(^3\) carbons, the dominant sp\(^2\) structure is preserved allowing fast electron transfer to the redox active surfaces. The lithium ions can transport quickly into and out from the interior regions thanks to the preserved mesoscale channels regardless of the partial collapse. As a consequence, the oNPC cathode demonstrated excellent high rate capacity. In the meantime, the lithium storage should be located on the defect or edge sites rather than on the basal plane since the basal epoxide is unlikely present.

Figure 6. Schematic illustration of the epoxidation and lithium storage of the oxidized nanoporous carbons.
4. Conclusions

Functional nanoporous carbons with aligned mesoscale channels were prepared from epoxidation process. The turbostratic carbon structure of this nanoporous carbon cannot maintain as stable epoxide structure as graphite epoxide. The epoxidation treatment eventually generated more carbonyl and carboxyl groups that were decorated on both the exterior and inner surfaces of the carbon particles. The increment of electroactive oxygen groups results in the higher pseudocapacitive lithium-storage capacity (313 mA h/g@50 mA/g), which is comparable with the best ever graphene-based cathodes in literature. The oxidized nanoporous carbons also exhibited good stability and high rate performance indicating the application potential for high power and durable lithium ion capacitors. Further research can be directed towards the selection of proper nanoporous carbon matrix, such as nanoporous graphitized carbons, for the controlled synthesis of highly porous carbon/graphite epoxide for enhanced surface-driven storage of monovalent cations.

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References

Graphical Abstract

High-capacity pseudocapacitive Li storage on functional nanoporous carbons with parallel mesopores
Through epoxidation, an oxidized nanoporous carbon cathode with extraordinary pseudocapacitive Li-storage capacity was fabricated. The cathode showed improved rate performance as well as long-term stability that are beneficial for high power lithium ion capacitors.