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All-carbon-based cathode for a true high-energy-density Li-O_2 battery

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ABSTRACT

Li-O_2 batteries have a high theoretical energy density; however, their current cathode system based on a heavy metal framework strikingly diminishes their real energy density. Herein, we report the fabrication of all-carbon-based cathodes composed of conventional active carbon and a carbon mesh (CM) framework produced from waste silk fabric by simple pyrolysis. CM frameworks show a high electrical conductivity of ~150 S cm^{-1}, good tensile strength of 34.1 ± 5.2 MPa, and a Young's modulus of 4.03 ± 0.7 GPa, as well as a well-ventilated ordered macroporous structure. These all-carbon-based cathodes exhibit stable cycling and high energy densities of ~2600 Wh kg^{-1} based on total electrode weight, which are 4–15 times higher than those of conventional air cathodes.

1. Introduction

The environmental impact of fossil fuels along with the rising demand for high-energy storage systems have driven researchers to develop renewable and eco-friendly power sources. Unfortunately, Li-ion batteries (LIBs), the predominant power source so far, are not suitable for large-scale applications such as electric vehicles (EVs) and hybrid electric vehicles (HEVs) owing to their low energy density. Therefore, further research has examined alternative power sources with high energy density and renewable green chemistry. Among several candidates, the Li-O_2 battery has attracted considerable attention due to its ability to utilize atmospheric oxygen [1–7]. The direct reaction between Li ions and O_2 ($2Li^+ + O_2 + 2e^- \rightarrow Li_2O_2$) does not require heavy transition metal hosts and is therefore attractive for large-scale energy storage systems [8–10].

The in situ formation and decomposition of the solid discharge product, lithium peroxide (Li_2O_2), during electrochemical charge and discharge is a unique characteristic of Li-O_2 batteries [11–13]. The discharge product is an insulator and inhibits rapidly progress of occurring reaction. This is an important consideration in the selection and production of cathode containing an active carbon material with high specific surface area. Accordingly, a porous cathode with a well-ventilated framework is required to accommodate the solid discharge products and avoid early clogging of the air cathode. To accomplish this, robust electrode designs with hierarchical pore structure have been developed, utilizing active carbon and a metal mesh substrate such as nickel, aluminum, or stainless steel [14–16]. However, the use of heavy metals can cause a serious loss in the overall energy density of Li-O_2 batteries. Most reported energy densities of Li-O_2 batteries are significantly overestimated, since they are calculated based on the weight of active carbons only. Therefore, a lighter, more robust, and well-ventilated framework substitute for the heavy metal mesh would greatly improve future high-energy-density Li-O_2 batteries. Nevertheless, this issue remains unsolved in the Li-O_2 battery society.

Carbon-based compounds are valuable alternative substrates for Li-O_2 batteries, due to their light weight, high conductivity, chemical and thermal stability, good mechanical properties, and affordability. Although conventional carbon papers have recently been adopted, a more ordered macroporous structure and a lighter framework are required when using these materials as a substrate

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for the Li-O_2 battery cathode. Moreover, considering scalable production, the development of a simpler eco-friendly process with unique material characteristics is also important.

This study highlights the development of a high-energy-density Li-O_2 battery using all-carbon-based cathodes composed of carbonaceous meshes (CMs) and active carbons such as Ketjen black (KB) and purified carbon nanotubes (*p*-CNTs). CMs have a hierarchical pore structure and are formed by simple heating of waste silk fabric (WSF). This fabric is about 20 times lighter than a conventional metal mesh, and heating greatly enhances its specific energy density. CMs possess favorable mechanical properties as well as chemical and thermal stability, achieving good electrochemical performance of all-carbon-based cathodes for Li-O_2 batteries.

2. Experimental

2.1. Fabrication of CMs

Mesh organdy silk fabric was purchased from the Dongdaemun Shopping Complex in South Korea and boiled for 30 min in a 0.02 M aqueous solution of Na_2CO_3 (99%; OCI Co.). The fabric was thoroughly rinsed with deionized water to extract the impurities. After drying at room temperature for 72 h, the silk fabric was carbonized in a furnace at temperatures from 800 to 1600 °C. After washed with ethanol and followed by deionized water, to remove residual water, the samples were subsequently heated to 150 °C for 2 h at a rate of 5 °C min^{-1}, followed by a 2 h at the desired temperature under an argon atmosphere (minimum purity: 99.9990%; gas flow: 100 cm^3 min^{-1}). The resulting CMs were stored in a desiccator.

2.2. Preparation of p-CNTs

Commercial CNTs (CM-250, Hanwha Chemical, Korea) were immersed in 60% HNO_3 solution at 60 °C and stirred for 3 h. After vacuum filtration, the samples were washed with deionized water until neutral pH. The obtained CNTs were subsequently dried in an oven at 30 °C and then heated at a rate of 5 °C min^{-1}, followed by a 2 h isotherm at 1000 °C under an argon atmosphere (minimum purity: 99.9990%; gas flow: 100 cm^3 min^{-1}). The resulting *p*-CNTs were stored in a desiccator.

2.3. Cell configurations

The air electrode was composed of KB (EC 600JD) or *p*-CNTs with Kynar 2801 binder (8:2 wt ratio) on several types of current collectors. The KB and binder were mixed into a paste using a mortar and pestle, rolled to uniform thickness, and dried in a convection oven at 120 °C. The *p*-CNTs and binder were prepared using the same method; however, the mixture was dried at −50 °C and 0.0045 mbar using a lyophilizer for 48 h after freezing at −196 °C. Ni mesh, Ni foam, and Al mesh (Nillaco Corp., 12.7 mm diameter) were used as current collectors. A Swagelok-type Li-air cell was prepared in the following sequence: Li metal anode, separator (Whatman GF/D microfiber paper), and the prepared air cathode. Lithium bis(trifluoromethane)sulfonimide (LiTFSI, 1 M) in tetraethylene glycol dimethyl ether (TEGDME) was used as the electrolyte, and all cells were tested in an atmosphere of pure oxygen (770 Torr outer pressure) using a potentio-galvanostat (WonA Tech, WBCS 3000, Korea) at a current density of 0.2 mA cm^{-2}. All electrode components were fully soaked with electrolyte, and the cells were relaxed for 0.5 h before testing. The cyclability of the CM-KB electrode was evaluated with a capacity limit of 0.5 mAh at a constant rate of 0.2 mA cm^{-2}.

2.4. Characterization

The morphologies of CMs and *p*-CNTs were examined by field-emission scanning electron microscopy (FE-SEM; Philips, XL 30 FEG, Eindhoven, Netherlands) and field-emission transmission electron microscopy (FE-TEM; JEOL, JEM2100F, Japan). Raman spectra were recorded using a linearly polarized continuous-wave laser (wavelength: 514.5 nm; 2.41 eV; power: 16 mW). The laser beam was focused by a $\times 100$ objective lens, resulting in a spot of ca. 1 μm diameter. An acquisition time of 10 s and three scans were used to collect each spectrum. X-ray diffraction (XRD; Rigaku DMAX 2500) was carried out using Cu K_α radiation ($\lambda = 0.154$ nm) at 40 kV and 100 mA. X-ray photoelectron spectroscopy (XPS; PHI 5700 ESCA, Chanhassen, MN, USA) with monochromatic Al K_α radiation ($h\nu = 1486.6$ eV) was used to examine the chemical composition of the samples. The mechanical properties were tested using an Instron 4665 ultimate tensile testing machine (UTM) at 20 °C and 30% humidity. The porosity of *p*-CNTs was analyzed using nitrogen adsorption and desorption isotherms obtained based on the surface area, using a porosimetry analyzer (ASAP 2020, Micromeritics, USA) at −196 °C.

3. Results and discussion

The schematic diagram in Fig. S1 shows that the metal current collector (the substrate of the air cathode) has the highest weight proportion (over 82 wt%) among all key components (including Li metal, electrolyte, separator, binder, and active material) of a conventional laboratory-scale single Li-O_2 cell (See Table S1 for more specific information). Nevertheless, a well-ventilated and ordered macroporous structure, along with hardness and electrochemical stability of the metal current collector, is necessary to stably accommodate the solid Li_2O_2 discharge products during cycling. In this respect, to substitute the heavy substrate with a light component, we designed a new light substrate (with a structure similar to that of the conventional metal current collector) using waste silk fabric (WSF). WSFs are well-organized by several threads and exhibit a macroporous structure [Fig. 1(a)]. Simple heating transformed WSFs into a carbonaceous material called pyroprotein [17,18], and their morphology was well-maintained even after heating at 1400 °C, with a small shrinkage [Fig. 1(b–d)]. The pore size and structure of CMs were similar to those of the conventional Ni mesh [Fig. S2]. However, it should be noted that the CM area density (2.5 mg cm^{-2}) was ~27 times smaller than that of conventional metal meshes (Ni mesh, 68.5 mg cm^{-2}).

CMs have poorly developed graphitic structures with 1~2-nm L_c and 2~4-nm L_a, calculated from XRD patterns and Raman spectra, respectively, with scarcely grown microstructures due to the increase of pyrolysis temperatures [Fig. 2(a) and (b)]. Increasing the heating temperature from 800 to 1600 °C caused the *D* and *G* bands in the Raman spectra of CMs to become narrower due to the development of sp^2-conjugated carbon structures. Furthermore, the electroconductivity of CMs increased with pyrolysis temperature due to the hexagonal carbon planes being more ordered [Fig. 3]. CM-800 and CM-1000 exhibited electroconductivities of ~0.4 and ~2.5 S cm^{-1}, respectively. The conductivity was remarkably increased for the heating temperature range of 1000–1200 °C, and CM-1200, CM-1400, and CM-1600 showed high electroconductivities of ~60, ~150, and ~300 S cm^{-1}, respectively [Fig. 3].

The mechanical properties of CMs also changed with increasing temperatures [Table 1]. The CM tensile strength and Young's modulus increased dramatically between 1000 and 1200 °C and between 1200 and 1400 °C, respectively. As a result, CMs prepared