Tailoring carbon nanomaterials via a molecular scissor

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A B S T R A C T
Carbon is a fascinating element that can be found in a wide spectrum of materials and plays a significant role in diverse disciplines across the scientific community. Carbon nanomaterials take many forms with numerous applications. Controllably tailoring carbon nanomaterials at the molecular scale can be considered as a basic innovation yet remains a significant challenge because of carbon’s intrinsic structural and chemical stability. Herein, we report a molecular scissor to efficiently tailor carbon nanomaterials of different dimensions at a molecular level. By using the Mg/Zn bimetallic effect and CO2 molecules, a molecular scissor was invented to engineer the surface of carbon nanomaterials with highly interconnected graphene pillared superstructures. The molecular scissor redesigned the carbon materials with improved surface properties for use in various applications. For energy storage application, both ultrahigh surface area and conductivity can be achieved concurrently with substantial ion-reserved accommodation and rapid mass-transfer expressway. As a demonstration, a flexible solid-state supercapacitor based on the surface-tailored carbon fiber was developed with Polyvinyl alcohol(PVA)/Na2SO4 gel electrolytes. It delivered a remarkably high energy density of 4.63 mWh cm−2 at a power density of 3520 mW cm−2. This work paves a new way to reinvent carbon materials at the molecular scale and promote their applications for energy storage, sensing, environmental remediation, and healthcare.

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Introduction

Carbon materials are of paramount importance to modern science and technology. Over the last three decades, extensive efforts have been made to explore new allotropes of carbon materials [1–3]. Nanodiamonds, fullerenes, carbon nanotubes (CTNs), graphene, and carbon quantum dots have been sequentially discovered and received significant attention from the scientific community because of their unique electrical, mechanical, optical, thermal, and chemical properties [4–12]. These properties, fundamentally determined by the intrinsic structure and bonding of carbon atoms, have paved the way for many innovations in different areas of modern science and technology including energy [13–18], sensing [19,20], and environmental remediation [21].

Carbon nanomaterials are widely used for the nanotechnological applications in energy, sensing, environment and biomedical fields [22]. The controllable construction at a molecular level is considered to be one of the key parameters to determine the structure of nanomaterials. Therefore, carbon nanomaterials surface engineering has become extremely important. As is known, surface engineering is an indispensable and fundamental approach to further improve the performance and expand the application fields of various carbon nanomaterials [23,24]. Although methods to modify a certain carbon allotrope for specific applications have been reported in previous literature, there are currently no facile and universal approaches to tailor carbon nanomaterials of different dimensions with desirable properties [25,26]. From the perspective of modification methods, high-temperature heat-treatment or use of strong oxidant are widely accepted methods yet possesses the fatal drawbacks that the former reduces specific surface area (SSA) and the latter increases of resistivity [27,28]. Additionally, the modified carbon structures tend to be more random in nature with no controllability at a molecular level. From the perspective of targeted materials, anisotropic 1D and 2D carbon nanomaterials are difficult to modify at the molecular level because eliminating their strong π-π stacking can lead to the entanglement phenomena of graphene elements found in nature [29–31]. Hence, there

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still lacks an efficient and ubiquitous method to rationally modulate pre-existing carbon nanomaterials of different forms which can realize desired surface properties.

Here, we report a controllable tailoring strategy to pervasively modulate carbon nanomaterials ranging from zero-dimensional (0D) to three-dimensional (3D) structures through a molecular scissors method. The molecular scissors, consisting of Mg, Zn, and CO₂ molecules, can open up the outer walls of carbon nanomaterials and enable the growth of defect-rich graphene petals on the surface. As a result, the properties of the carbon nanomaterials, including its SSA, defect density, functional groups, thermal and electrical properties, can be effectively tailored for a wide range of desirable applications. For energy storage applications, both ultrahigh surface area and conductivity can be achieved concurrently with substantial ion-reserved accommodation and rapid mass-transfer expressway. A tailored tubular superstructured nanocarbon (TSNC) supercapacitor was fabricated with a high-power density of 3520 mW cm⁻³ and a high energy density of 4.63 mWh cm⁻³ simultaneously, outperforming most existing carbon based supercapacitors. The controllable tailoring strategy will provide a new route to reinvent carbon nanomaterials at a molecular level and further exploit and extend their applications in energy storage, catalysis, medical therapy and environmental remediation.

Results

Molecular scissors tailoring process

Our strategy involves having bimetallic Mg/Zn vapors and CO₂ molecules co-play the scissors role to elaborately avoid uncontrollable π-π interactions. As shown in Fig. 1a-d, at high temperatures (e.g., 700–800 °C), the strong chemical reactivity of the bimetallic metal vapors promotes their reaction with hierarchical carbon tubular nanostructures (hCTNs), which can be experimentally authenticated by the Mg/Zn particles anchored both on the surface (Fig. S1) and in the interior of hCTNs (Fig. S2). Once CO₂ is introduced, the molecular scissors will tailor the carbon nanomaterials as following equations:

\[ \text{CO}_2(g) + C(s) \rightarrow 2\text{CO}(g) \]  
\[ 2\text{Mg}(l) + \text{CO}_2(g) \rightarrow 2\text{MgO}(l) + C(s) \]  
\[ \text{Zn}(g) + \text{CO}_2(g) \rightarrow \text{ZnO}(l) + \text{CO}(g) \]

Without the addition of Zn powder (i.e. only Mg powder) under the introduction of CO₂, the carbon particles could not only be coated on the surface of hCTNs, but also clearly open up the surface of hCTNs (Fig. S3). While without the addition of Mg powder (i.e. only Zn powder), the surface of hCTNs has been successfully opened, as shown in the scanning electron microscopy (SEM) (Fig. S4) and transmission electron microscopy (TEM) (Fig. S5). As a consequence, with the addition of Zn powder under the absence of CO₂, the Zn particles enter the interior of the hCTNs to prepare for tailoring the carbon nanomaterials and inducing the growth of graphene sheets (Fig. S6). Therefore, the Mg/Zn and CO₂ molecular scissors work together to open the close axial surface of hCTNs. Afterwards, Zn plays a catalytic role for the epitaxial growth of pillared graphene layers. Fig. 1d and f compares the TEM images of hCTNs before and after the tailoring process. It can be seen that highly interconnected graphene pillared superstructures are successfully built on the opened surface of hCTNs. These highly interconnected surface superstructures combining different low-dimensional nanocarbons ideally possess desirable in-plane—and more importantly, out-of-plane—properties since the latter is inevitably deteriorated by weak Van der Waals interaction. It is worth noting that a combination of the bimetallic effect of Mg/Zn and the confinement template of hCTNs is necessary for the tailoring process.

This molecular scissors engineering process is universal to various allotropes of carbon materials. For example, beside hCTNs, multi-walled CNTs (MWCTNs, Fig. 1g) and activated carbons (ACs, Fig. 1i) can also be sheared into carbon superstructures (Fig. 1h and j) in which the surface of carbon matrices become an open structure with pillared graphene layers. More TEM images of the tailored MWCTNs and ACs in Fig. S7 and S8 reveal that the open structures of the carbon matrix with anchored pillared graphene on the surface of the carbon matrix modifies the surface properties of carbon nanomaterials significantly. Specifically, high SSA and short ion diffusion length can be achieved without sacrificing electric conductivity, which is impossible with previously reported tailoring methods. Therefore, in comparison with their carbon matrices (Fig. 1b), such unique carbon superstructures effectively guarantee substantial ion-reserved accommodation and rapid mass-transfer expressway (Fig. 1c).

After understanding the principle and function of the molecular scissors, a novel carbon nanomaterial called the quasi-one-dimensional tubular superstructure of nanocarbons (q-1D-TSNCs) can be controllably constructed and tailored at 750 °C as shown in Fig. 2. Fig. 2a-c schematically presents the controllable building process of q-1D-TSNCs on stainless steel mesh (please see the Methods section for more detailed information). First, the smooth surface stainless steel mesh (Fig. 2d) serves as the supporting substrate for synthesizing hCTNs by conversion of CO₂ using Mg metal as a reducing agent [32]. As shown in Fig. 2e, the as-prepared hCTNs exhibits a smooth and close axial surface. Further shearing the surface of hCTNs with molecular scissors obtained a fully opened microstructure that would extract their ion-reserved and transport characteristics. Hence, the synergistic effect of the bimetallic Mg/Zn and CO₂ molecules smartly plays a scissors role of opening the close axial surface of hCTNs t to create the highly interconnected 3D q-1D-TSNCs, as demonstrated in SEM images of Fig. 2f and Fig. S9.

For further insight into the highly interconnected microstructures of q-1D-TSNCs, TEM images were taken, revealing the insertion of carbon nanosheets (Fig. 2g and 2h) [33]. Remarkably, these carbon nanosheets possess a high degree of crystalline structure, which is mainly attributed to the participation of Zn vapor at high temperature (Fig. 2f and Fig. S10). On the contrary, the inner core of hCTNs exhibits a porous structure that originates from the removal of metal oxides like ZnO and MgO (Fig. 2i) [34,35].

As shown in Fig. S11, the energy dispersive X-Ray spectroscopy (EDS) mapping measurements of the as-prepared TSNCs further confirms that no Mg and Zn are present (less than 0.1 %), therefore indicating the high carbon purity of 3D TSNCs. Also, X-ray photoelectron spectroscopy (XPS) analysis in Fig. 2k and Fig. S12 confirm the high atomic percentage of carbon (∼94 %), accompanied with some terminated oxygen groups (∼6%), such as C=O, C=O, —= and COOH [36]. Notably, transition metals such as Fe or Mn were not observed, suggesting that the formation of TSNCs is not related with the catalysis of transition metals, but originated from the synergistic action of the Mg/Zn bimetallic effect and CO₂ molecules.

Tailoring parameters such as temperature and time can desirably modify the shape, size, and density of carbon superstructures. As shown in Fig. 3a, d and g, besides q-1D-TSNCs, carbon nanostructures such as zero-dimensional carbon spheres (0D-CSs) and one-dimensional tubular superstructure of nanocarbons (1D-TSNCs) can be successfully created at different aimed reaction temperatures (700 °C, 750 °C and 800 °C, respectively) via balancing the role of molecular scissors and their following oriented growth. Previous investigations on carbon nanotube and graphene catalytic growth on metal surfaces shed light on the importance of balancing this relationship [37,38]. At a relatively low temperature like 700 °C, graphene or CNT formation could not keep up with the car-
A carbon atom supply at the catalytic surface. As a result, 0D carbon spheres grow is observed as shown in Fig. 3a. The SEM images in Fig. 3b and c further imply carbon spheres randomly segregate at the networks of hCTNs. B. Besides, at relatively high temperatures such as 800 °C, both scissors originating from Mg/Zn metals and CO2 molecules possess an extremely strong reactivity. Once encountered, the metals can immediately capture the oxygen free radicals to form chemically active carbon dangling bonds. These dangling bonds formed at the initial stage serve as the soot that is made up of three layers of carbon and is deposited at the hCTNs to form new carbon nanomaterials. As demonstrated in Fig. 3d-f for q-1D-TSNCs and Fig. 3 g-i for 1D-TSNCs, pillared graphene layers precisely grow on the surface of hCTN precursors, leading to unique TSNCs. The difference between q-1D-TSNCs and 1D-TSNCs is that the graphene layers are loose at the optimal temperature of 750 °C while at a higher temperature they become much denser due to the much more rapid nucleation for the latter (Fig. S13).

Fig. S14 shows SEM images of TSNCs prepared at different reaction times (20, 40 and 60 min) obtained at 700 °C. With longer tailoring time, the network structure of TSNCs becomes more and more compacted while still maintaining the tubular superstructure. In addition, the X-ray diffraction (XRD) patterns in Fig. S15 indicate that the crystallinity of the TSNCs can be easily tailored by controlling the activity of the molecular scissors. Moreover, the high activity of Zn/Mg vapors generated at elevated temperatures further increases the defects of TSNCs, which can be proved by Raman spectra characterization in Fig. S16. Evidently, these TSNCs contain abundant structural defects that are indicated by a sharply broadened peak at the center of the Raman peak at about 1350 cm⁻¹. By calculating the area of the D-band and G-band after multi-peak fitting through Voigt function, the I_D/I_G of the hCTNs, 0D-CSs, q-1D-TSNCs, and 1D-TSNCs are 1.43 ± 0.05, 2.36 ± 0.02, 2.25 ± 0.01, and 2.18 ± 0.02, respectively, which further implies high ratio of defects (Fig. S16).

**TSNC-based supercapacitors for energy storage applications**

Since the TSNCs have an entirely open nanostructure (Fig. 4a), they are anticipated to have improved mass transfer capability. As shown in Fig. 4b, the N₂ adsorption/desorption isotherms of TSNCs are typical type IV, indicating hierarchical carbon tubular nanotextures with combined micro- and meso-pores. As illustrated in Fig. 4c, the q-1D-TSNCs yield a reasonable pore size distribution and an optimized high SSA of 1685 m² g⁻¹, whereas OD-CSs and 1D-TSNCs demonstrate lower SSA of 1032 m² g⁻¹ and 1065 m² g⁻¹, respectively.

The as-prepared TSNCs are assembled with PVA/Na₂SO₄ gel electrolyte toward the symmetric flexible solid-state supercapacitor with excellent mechanical flexibility as shown in Fig. 4d, e and Fig. S17. Due to the high electrochemical stability of PVA/Na₂SO₄ gel electrolyte, the supercapacitors can be reversibly charged/discharged up to 1.6 V without apparent excessive polarization (Fig. S18). Fig. 4f and Fig. S19 demonstrate cyclic voltammetry (CV) curves of the supercapacitors with a near-rectangular shape, indicating a double-layer energy storage mechanism. The maximum areal capacitance for q-1D-TSNCs is 171 mF cm⁻² (684 m F cm⁻² for a single electrode) at 5 mA cm⁻² (Fig. 4g). When the current density is increased to 40 mA cm⁻², 82.7 % specific capacitance can be retained, indicating an excellent rate-capability of this supercapacitor (Fig. S20).

Fig. 4h presents the Nyquist plot of the three different TSNCs. Although Na₂SO₄ electrolyte possesses intrinsically lower ionic conductivity and larger ionic size than KOH or H₂SO₄, the internal resistance is only about 3.65 Ω when PVA/Na₂SO₄ gel electrolyte is assembled with these unique TSNCs. In the low frequency region, a nearly vertical line (81°) evidently indicates their excellent capacitive characteristics. The small diameter of the semicircle in high frequency range and the near absence of the Warburg region imply rapid charge transfer and ionic diffusion as a result of the open structure created via the molecular scissors method. Fig. S21 demonstrates the cyclic stability of the q-1D-TSNCs supercapacitor at 10 mA cm⁻². More than 80 % capacitance can be retained after 5000 cycles.

Fig. 4i and j display the volumetric and areal Ragone plots of TSNCs-based supercapacitors, respectively. It can be seen that TSNCs-based supercapacitors demonstrate extraordinary volumetric energy density of 4.63 mWh h cm⁻³, even at a high volumetric power density of 3520 mW cm⁻³. When calculated based on surface area, its energy density reaches up to 60.7 µWh cm⁻², accompanied with a power density of 4 mW cm⁻². When the areal power density dramatically increases by 700 %, the areal energy density remains 41.7 µWh cm⁻² due to the remarkable rate capability. These results
are superior than previously reported carbon nanomaterials based symmetric supercapacitors, mainly due to the enlarged surface area and short ion diffusion length owing to the molecular scissor. A more detailed comparison of TSNCs-based supercapacitors and devices in previous literature is shown in Table S1. It is clear that TSNCs-based supercapacitors display a wide voltage range and considerable areal capacitance, therefore having outstanding energy density—an important property for practical applications. Finally, the optical images of Fig. 4k and l demonstrate that TSNCs-based supercapacitors can be connected in series or in parallel to meet higher voltage or capacitance requirements. As indicated by Fig. 4m and n, two TSNCs-based supercapacitors in series enable an operating voltage of 3.2 V, while two TSNCs-based supercapacitors in parallel enable doubled areal capacitance, indicating a high voltage or high current output. In summary, rationally constructed carbon tubular superstructure via molecular scissors not only results in excellent rate capability and cyclical stability, but also promotes both high energy density and high power density.

The outstanding electrochemical performance of TSNCs-based supercapacitors is attributed to its combination of superior electronic conductivity, ionic transportation, and its highly interconnected 3D superstructures toward efficient promotion of substantial ion-reserved accommodation and rapid mass-transfer expressway. First, the pillared graphene grown on hCTNs forms a core-shell structure for addressing the critical issue of the weak van der Waals interaction along the perpendicular direction between the graphite layers. Therefore, the pillared graphene shell can act as an ‘expressway’ to promote mass transfers, while the hCTNs core with high SSA can serve as an ‘accommodation’ to provide an ion reservoir. In addition, the hierarchical pore distribution of hCTNs cores with a large number of substantially ion-reserved accommodations increase the ion-accessible SSA to form an electric double-layer capacitance. Furthermore, the stainless-steel mesh can not only be used as a conductive substrate to support the nanocarbons, but also be directly used as the current collector in supercapacitors for exhibiting flexibility and mechanical strength.
Fig. 3. Construction of carbon nanomaterials with different dimensions by the molecular scissors. (a, d, g) Schematics illustrating the role of molecular scissors and their growth in yielding zero-dimensional carbon spheres (0D-CSs), quasi-one-dimensional tubular superstructure of nanocarbons (q-1D-TSNCs), one-dimensional tubular superstructure of nanocarbons (1D-TSNCs). (b, e, h) The representative SEM images of 0D-CSs, q-1D-TSNCs, and 1D-TSNCs samples. (c, f, i) The enlarged SEM images.

More importantly, the molecular scissors can be easily extended to tailor all kinds of different dimensional carbon nanomaterials, which will promote their extended applications in energy storage, catalysis, sensing, medical therapy, and environmental remediation.

Conclusion and perspective

In summary, we developed a molecular scissor capable of tailoring and constructing advanced carbon nanomaterials of different dimensions at a molecular level. Regarding the molecular scissor, Mg/Zn and CO$_2$ molecules co-played the scissor role to open up the surface of carbon nanomaterials and enable the growth of graphene petals. This dual mechanism ultimately leads to uniquely structured carbon nanomaterials such as the quasi-one-dimensional tubular superstructure of nanocarbons (q-1D-TSNCs), which exhibits drastically improved surface properties including SSA, defect density, functional groups, and thermal and electrical properties. Specifically, TSNCs constructed and tailored with the molecular scissor with a high SSA of 1685 m$^2$ g$^{-1}$ and rapid channels of electron transfer were further studied for energy storage applications. A TSNCs-based flexible solid-state supercapacitor was able to deliver a high power density of 3520 mW cm$^{-3}$ and high energy density of 4.63 mW h cm$^{-3}$ simultaneously, outperforming most existing supercapacitors with carbon nanomaterials.

Unambiguously, this promising work demonstrates that the universality of molecular scissors will bring a new renaissance of carbon nanomaterials and address the long-term issue of limited mass transportation that pervasively exists in many engineering fields.

Methods

Preparation of hierarchical carbon tubular nanostructures (hCTNs)

The hCTNs were synthesized with a simple method involving the reaction of Mg with CO$_2$ gas. To fabricate different substrates supporting hCTNs, Mg powders with a purity of 99.5 % was uniformly dispersed on stainless steel mesh substrate (500 meshes). In a typical process, 4.0 g of Mg powder were put into a high purity corundum boat (99.99 % in purity) with a size of 100 × 25 × 20 mm. Afterwards, the corundum boat was put into a tube furnace (GSL-1700X, Hefei Kejing Materials Tech. CO., Ltd., China) with a multichannel flow controller (GMF-2Z, AnHui BEQ Equipment Tech. CO., Ltd. China). After the Mg powder was heated to the aimed reaction temperature under the protection of Ar gas with a flow rate of 40 sccm, 40 sccm CO$_2$ was continuously introduced for an hour. After naturally cooling to the room temperature, the samples were taken out. Then, 1 M HCl aqueous solution was used to eliminate the Mg and MgO impurities. Finally, the samples were washed enough times by abundant deionized water and alcohol in sequence and naturally dried.
Molecular scissors for nanocarbons (0D-CSs, q-1D-TSNCs and 1D-TSNCs)

The as-obtained hCTNs were used as the confined assembling template to prepare nanocarbons. In a typical procedure, the uniform mixture of 2.0 g Mg powders (Tianjing Kernel Chemicals Reagent Co., Ltd., China) and 2.0 g Zn powders (Tianjing Kernel Chemicals Reagent Co., Ltd., China) was evenly-distributed in the corundum boat (99.95 % in purity). When the boat was heated up to different aimed reaction temperatures (700 °C, 750 °C and 800 °C) at a heating rate of 4 °C min⁻¹ under Ar atmosphere (40 sccm), Ar gas was rapidly cut down to 20 sccm and an additional CO₂ flow of 20 sccm was introduced immediately. After naturally cooling to the room temperature over 8 h, the sample was taken out. Then, 1 M HCl aqueous solution (Chengdu Kelong Chemicals Co., Ltd., China) was used to remove the impurities at room temperature for 10 h. For convenience, the obtained samples were denoted as 0D-CSs, q–1D-TSNCs, and 1D-TSNCs.

Molecular scissors for multi-walled carbon nanotubes

Multi-walled carbon nanotubes (Suzhou Carbon Rich Graphene Technology Co., Ltd., China) were uniformly pressed on a stainless-steel mesh substrate (500 meshes). In a typical procedure, the uniform mixture of 2.0 g Mg powders and 2.0 g Zn powders were evenly-distributed in the corundum boat (99.95 % in purity). When the boat was heated up to the aimed reaction temperature (750 °C) at a heating rate of 4 °C min⁻¹ under Ar atmosphere (40 sccm), the Ar gas was rapidly cut down to 20 sccm and an additional CO₂ flow of 20 sccm was introduced immediately. After naturally cool-
ing to the room temperature, the sample was taken out. Then, 1 M HCl aqueous solution was used to remove the impurities at room temperature for 10 h.

**Molecular scissors for activated carbon**

Activated carbons (Kuraray Chemical Co., Ltd., Japan) were uniformly pressed on a stainless-steel mesh substrate (500 meshes). In a typical procedure, the uniform mixture of 2.0 g Mg powder and 2.0 g Zn powder were evenly-distributed in the corundum boat (99.95% in purity). When the boat was heated up to the aimed reaction temperature (750 °C) at a heating rate of 4 °C min⁻¹ under Ar atmosphere (40 sccm). The Ar gas was rapidly cut down to 20 sccm and an additional CO₂ flow of 20 sccm was introduced immediately. After naturally cooling to the room temperature, the sample was taken out. Then, 1 M HCl aqueous solution was used to remove the impurities at room temperature for 10 h.

**Characterization methods**

A JEOL JSM-7800 Prime scanning electron microscopy (SEM) with an accelerating voltage of 5 kV and a JEOL JEM-2100 F transmission electron microscopy (TEM) were used to characterize the morphologies of the samples. XRD patterns were obtained using a PANalytical XPert powder diffractometer with Cu Kα source and 2θ from 10° to 80°. XPS analysis was performed on Thermo Scientific ESCALAB 250Xi. The surface area and Density Functional Theory (DFT) pore size distribution measurements of TSNC powders scraped off from the stainless steel was characterized by Micromeritics ASAP 2020 surface area and pore size analyzer using N₂ adsorption/desorption isotherm at −196 °C. Raman spectrum was conducted on RMM2000 microscopic confocal Raman spectrometer employing a 514 nm laser beam.

**Fabrication of Flexible solid-state supercapacitors**

The PVA-Na₂SO₄ gel electrolyte was assembled with two TSNC electrodes for the flexible solid-state supercapacitors. Firstly, PVA-Na₂SO₄ gel electrolyte was prepared through mixing the PVA (1799 type, 5 g) and deionized water (45 mL) in the water bath kettle at 90 °C until clear. Then, the Na₂SO₄ aqueous solution (20 mL, 1 M) was slowly added into the PVA colloso at room temperature. Polydimethylsiloxane and silicone elastomer-curing agent (PDMS, Dow Corning Corporation) with a mass ratio of 5:1 was used to package the supercapacitors after vacuum removal of the bubbles. After that, EIS (frequency range from 0.01 Hz to 1,000,000 Hz), CV (scan rate from 20 mV s⁻¹ to 500 mV s⁻¹) and GCD (current density from 5 mA cm⁻² to 40 mA cm⁻²) tests were conducted on a CHI660E electrochemical workstation (Chenhua, Shanghai, China) and a cycling lifetime test was carried on an Arbin MSTAT4 multi-channel galvanostat/potentiostat instrument.

**Availability of data**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Author contributions**

J.C., W.Y. and H. Z. planned the study and guided the whole project. W.Y., J.C., H. Z., Q.W., and Y. Z. conceived the idea, designed the experiment, analyzed the data, drew the figures, and composed the manuscript. Q.W., Y. Z., K. Z. K. C., B.G., and T.Y. performed the measurement and made technical comments on the manuscript. Q.W. and Y. Z. contributed equally to this work. J.C. submitted the manuscript and was the lead contact.

**Declaration of Competing Interest**

The authors declare no competing financial interest.

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**Appendix A. Supplementary data**

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