

# The construction of an asymmetric hybrid supercapacitor with 2D materials MXene and perovskite

Yile Yang

Tongji University, 4800 Cao'an Road, Jiading District, Shanghai, China

lukasyang23@gmail.com

**Abstract.** The traditional energy storage techniques have several initial drawbacks limiting this application. Batteries suffer from a slow charge and discharge rate, and capacitors have low energy densities. The pseudocapacitor, a technology that stores energy through surface chemical reactions, is supposed to fill the energy and power density gap between the dielectric capacitor and battery. In order to verify the superiority of this technology, an asymmetric hybrid supercapacitor has been designed with 2D material MXene ( $\text{Ti}_3\text{C}_2\text{T}_x$ ) as the negative electrode and high-entropy perovskite-type materials ( $\text{La}(\text{CoCrFeMnNi})\text{O}_3$ ) as the positive electrode. XRD has verified the crystallography of both electrode materials, and the morphology has been further studied by SEM, TEM, and HAADF-STEM. The electrochemical performance has been tested by CV, GCD, and EIS. Besides, the influence of the different elements of the high-entropy perovskite has been studied. The asymmetric supercapacitor shows both high energy and power density, which may be used to extend energy-storage technology applications.

**Keywords:** Pseudocapacitor, asymmetric supercapacitor, 2D materials, perovskite

## 1. Introduction

Several energy-storage technologies have been proposed and utilized in different applications to fulfil the energy requirement of electronic vehicles, portable devices, and power grid storage. Presently, the most mature technologies are lithium batteries and capacitors, which have been large-scale used in electronic vehicles and circuit boards. However, lithium batteries have low charging rates and short lifespans, which restrict their more far-reaching application, and the energy densities of capacitors are too low, which makes it impossible to act as a storage container for large-scale electrical energy [1]. To fill in the large energy density and power density gap between conventional electrochemical batteries and dielectric capacitors, electrochemical capacitors (ECs, so-called supercapacitors) have become the most attractable energy container thanks to their considerable energy density, fast charging rate. Besides, their lifespan is almost infinite. Based on their charge-storage mechanism, ECs can be further classified into electric double-layer capacitors (EDLCs) and pseudocapacitors. EDLCs, which store charges in double layers at the electrode/electrolyte interface via a non-faradic and pure physical process, have a significant high-power density and can complete a charge-discharge cycle in seconds [2]. Unfortunately, the charge-storage capacity relying on the electrosorption of ions is strictly limited by the electrode's surface area. Pseudocapacitors, which is another subclass of ECs, exhibit redox reactions (as same as battery) as fast as the formation of double layers in EDLCs. As a result, pseudocapacitive materials represent a higher charging rate (comparing with batteries) and a larger energy density than EDLCs [3].

However, the applications have been impeded by several shortages of current pseudocapacitive materials, such as limited voltage windows, poor cyclic stability, and low electronic conductivity. Hence, the main goal is to design and synthesize high-performance electrode of pseudocapacitors with high power and energy density, decent electronic conductivity, and long cyclic lifespan [4,5].

Since the successful synthesis of graphene with single-layer twenty years ago, many scientists began to focus on two-dimensional (2D) materials because of their special properties, which cannot be found in their bulk counterparts. In 2011, scientists at Drexel University discovered 2D materials called MXenes, which have a general formula of  $M_{n+1}X_nT_x$  where M is a transition metal which could be scandium (Sc), zirconium (Zr), tantalum (Ta), or so on, X represents carbon, nitrogen or carbon and nitrogen, and  $T_x$  stands for the surface termination consisting of hydroxyl, oxygen or fluorine [6,7]. The superiorities of MXenes is their variable chemical composition and crystal structure. By selecting the type of element of M and X atoms, fabricating surface terminations (T), changing the number of layers ( $M_2X$ ,  $M_3X_2$ ,  $M_4X_3$ , or so on), and tuning flake size and concentration of defects, suitable materials can be synthesis as the electrode for pseudocapacitors [7]. The most studied MXene for electrochemical capacitors is  $Ti_3C_2T_x$ , which has an outstanding volumetric capacitance of  $300-400 \text{ Fcm}^{-3}$  [7].  $Ti_3C_2T_x$  electrode also has a perfect capacitive behavior (a box-like profile can be observed from a cyclic voltammogram curve) and excellent cyclic stability (little change in capacitance after 10,000 cycles).<sup>[7]</sup> Furthermore, via replacing F- terminations with O- terminations (decreasing pH value of electrolyte or using an HCl-NaF mixture to produce) and enlarging flake size, higher capacitance and electrical conductivity ( $4,600-6,500 \text{ Scm}^{-1}$ ) can reach.<sup>[7]</sup> However, irreversible oxidation of  $Ti_3C_2T_x$  occurs at a positive potential (0.2-0.4 V) [7]. It results in a narrow voltage window of a symmetric supercapacitor ( $\approx 0.6 \text{ V}$ ) [5]. Therefore, to expand the voltage window, a positive electrode has to be found to construct an asymmetric hybrid supercapacitor.

Perovskite-type materials are ideal positive electrodes of asymmetric supercapacitors because they are able to enlarge the voltage window and increase the energy density. Gustav Rose discovered perovskite as early as 1839, and later, it stands for a series of materials with a structure similar to that of calcium titanate [8]. Perovskite oxides ( $ABO_3$ ), one of the most noted perovskite-type materials, used to be treated as electrodes or electrolytes in batteries thanks to its ideal cubic symmetrical structure and decent ionic conductivity. In its general formula,  $ABO_3$ , A stands for an alkali earth or lanthanide element, and B is a transition metal [9]. This type of perovskite has several advantages, such as superior electronic structure, excellent ionic and electronic conductivity, and superb thermal stability. Furthermore, rapid faradic reactions can occur at the surface of  $ABO_3$ -type perovskite because of the existence of intrinsic oxygen vacancies, which makes them ideal candidates for pseudocapacitive electrodes [10]. Among them,  $LaMnO_3$  is attractive not only because of their good electrochemical behavior, environmental compatibility, and low cost but also due to the possible formation of nonstoichiometric content, which induces oxygen vacancies and structural distortion, and further enhances specific capacity, electrical conductivity, and ion diffusion rate [10,11]. For instance,  $LaMn_{1.1}O_3$  exhibits an excellent specific capacity of  $727.6 \text{ Cg}^{-1}$ , which is much higher than that of stoichiometric perovskite ( $411.8 \text{ Cg}^{-1}$ ) [11]. However, changes in stoichiometry also bring the defect of crystal structure and decline the life span of electrode materials. Constructing high entropy materials (HEMs) is a possible way to solve this problem while maintaining a distorting crystal structure. The entropy stabilization has been proved by the significant improvement of cycling stability and the Coulombic efficiency of rock-salt high-entropy oxides (HEOs) as the anode of lithium-ion batteries [12]. For instance, unlike traditional conversion materials, rock-type HEOs have a stable crystal structure that was partially maintained during the charge and discharge cycling and served as a permanent host matrix [13]. HEOs have also been employed as electrolytes in batteries because of their high ionic conductivity. Based on the charge compensation mechanism, oxygen deficiencies were created after inducing elements with different valences, which ensures quick ion movement and matches the demand of high-power rate in pseudocapacitance<sup>[14]</sup>. Besides, the multi-elements supply a multi-activated site and more couples of redox reactions, which may lead to a box-like profile in the CV (cyclic voltammetry) curve. So far,  $La(\text{CoCrFeMnNi})O_3$  has been synthesized and exhibits a complex magnetic state dominated by

antiferromagnetic interactions, which showed the possibility of constructing a perovskite high-entropy oxides and replacing B-site with five elements.<sup>[15]</sup> However, this research mainly focused on the magnetic behavior of the materials, and the electrochemical properties of this high-entropy material are also worth studying.

## 2. Synthesis and characterization

### 2.1. Synthesis of high-entropy perovskite (co-precipitation and thermal anneal method)

First, six kinds of solutions of precursors ( $\text{La}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ ,  $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{Cr}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ ,  $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ ,  $\text{Mn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ , and  $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ) were mixed with 20 mL of deionized water. The concentrations of all the solutions of precursors are 1M. According to stoichiometry, the volume of the solution of  $\text{La}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$  is 10 mL, and the volume of the other 5 solution is 2 mL each. Besides, 900 mg of glycine and 300 mg of Polyvinyl Pyrrolidone (PVP) were also added to the above mixture. To make sure all components were dispersed uniformly and dissolved totally, the mixture was further stirred for about 20 minutes. Then, 320  $\mu\text{L}$  of 28.0-30.0%  $\text{NH}_4\text{OH}$  solution was added into the mixed solution to adjust its pH value to about 8.9. The pH adjusted solution was then transferred into a 45 mL Teflon liner and placed in the autoclave. The mixture was heated at 180 °C for 12 hours in a box furnace and turned into solid state. After that, the solid mixture was washed three times with deionized (DI) water, centrifuged at rotate speed of 900 rpm for 10 minutes, and dried in a vacuum oven at 65 °C for 2 hours in a vacuum oven. Finally, the powder was calcinated at 600 °C (heating rate of 5 °C per minute) in a tube furnace for 2 hours to obtain the porous  $\text{La}(\text{CoCrFeMnNi})\text{O}_3$  particles. The porous particles turned into hollow nanospheres by an additional heat treatment at 650 °C for 2 hours under air.

### 2.2. Synthesis of MXene (MILD synthesis method)

Compared with the conventional synthesis route (clay  $\text{LiF}/\text{HCl}$  method), minimally intensive layer delamination (MILD) is a more desirable to synthesize single and larger flakes with fewer defects.<sup>[9]</sup> First, 8 g of  $\text{LiF}$  powder was added to 10 mL of 9 M  $\text{HCl}$ , and the mixture was stirred for 5 minutes to obtain the etchant. Then, 0.5 g of  $\text{Ti}_3\text{AlC}_2$  powder was slowly added to the etchant solution (over 5 minutes). At room temperature, the etching reaction was carried out for 24 hours. The reaction product was added by DI water and washed with centrifugation at a rotation rate of 3500 rpm for several cycles. A single centrifugation cycle lasted for 5 minutes. After each cycle, the acidic supernatant was decanted, and the same amount of fresh DI water was added for the next centrifugation. The centrifugation process ended when the pH value of the mixed solution reached 4 to 5. This pH range could be normally obtained by two centrifugation cycles using a 175 mL centrifuge tube or seven centrifugation cycles using a 50 mL centrifuge tube. At the end of the delamination process, a stable dark-green supernatant formed, and the  $\text{Ti}_3\text{C}_2\text{T}_x$  was deposited at the bottom of the centrifuge tube. To separate the  $\text{Ti}_3\text{C}_2\text{T}_x$  from  $\text{Ti}_3\text{AlC}_2/\text{Ti}_3\text{C}_2\text{T}_x$ , the black slurry was carefully collected with a spatula and filtered in a vacuum. Finally, the sample, which looked like a thick black cak, was dried in a vacuum at 120 °C for 24 hours to obtain a thick film of MXene.

### 2.3. Structural characterization of materials

The structure of as-prepared powder was exhibited by the X-ray diffraction (XRD) pattern. The test parameters of both two materials are same. The step size was set as 0.015°, the collection time was set as 4 s per step, the diffraction angle ( $2\theta$ ) range was set between 10 and 90°, and the voltage and the current were set as 30 kV and 40 mA, respectively. The morphologies of high-entropy perovskite and MXene were recorded by scanning electron microscope (SEM). With scanning TEM-energy-dispersive X-ray spectroscopy (STEM-EDX) and extended X-ray absorption fine structure (EXAFS), the elemental distribution maps of high entropy oxide were obtained. The nitrogen adsorption-desorption was also used to measure the Brunauer-Emmet-Teller (BET) specific surface areas of two samples. Furthermore, the surface electronic states of each chemical were identified by X-ray photoelectron spectroscopy (XPS).

#### 2.4. Preparation of electrodes

First, perovskite  $\text{La}(\text{CoCrFeMnNi})\text{O}_3$  powder, super-p-carbon, and polyvinylidene fluoride (PVDF) were mixed at a mass ratio of 80:10:10. The mixture was further dispersed in methylpyrrolidone (NMP) with ultrasounds, and a homogeneous slurry was produced. Next, the slurry-like mixture was spreaded on carbon paper in a size of 1 cm×1 cm uniformly. Finally, the positive electrode was obtained by drying the coated carbon paper at 60 °C for 8 hours in an oven. The negative electrode was prepared by the similar process. The only two differences between positive and negative electrodes preparation process are the mass ratio of MXene powder, super-p-carbon, and PVDF is 75:20:5 and the coated carbon paper was dried at 50 °C to obtain the working electrodes.

#### 2.5. Electrochemical measurements

Cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectrum (EIS) was employed to test the electrochemical properties by using the electrochemical workstation. Both positive and negative electrode materials were measured in an three electrode system consists with a working electrode (as-prepared samples) [2], a counter electrode (AC films), a reference electrode (Ag/AgCl), and an electrolyte (3 M KCl).

CVs were tested under several different scan rates (5-100  $\text{mVs}^{-1}$ ) in the potential range of 0-0.6 V and -0.8-0 V for  $\text{La}(\text{CoCrFeMnNi})\text{O}_3$  and  $\text{Ti}_3\text{C}_2\text{T}_x$  respectively. The gravimetric-specific capacitances ( $C_m$ ) of cathode and anode electrode were acquired by integrating the discharge portion of the CV curves following the equation (1):

$$C_m = \frac{\int I(V)dV}{ms\Delta V} \quad (1)$$

where s is scan rate and m is mass of active materials.

The specific capacitances were acquired from GCDs in which current densities are 1–5  $\text{Ag}^{-1}$  (for positive electrode material) and 0.5-10  $\text{Ag}^{-1}$  (for negative electrode material) using the equation (2):

$$C = \frac{\int I(t)dt}{m\Delta V} \quad (2)$$

In EIS measurement,  $\text{Ti}_3\text{C}_2\text{T}_x/\text{electrolyte}$  interface and  $\text{La}(\text{CoCrFeMnNi})\text{O}_3/\text{electrolyte}$  interface were approximated with an equivalent circuit model where a resistor and a capacitor are connected in series, and the frequencies is from 10 mHz to 10 Hz in a capacitive regime. The real capacitance ( $C'$ ), the imaginary capacitance ( $C''$ ) and phase angle ( $\Phi$ ) were calculated using the equation (3), (4), and (5), respectively.

$$C' = -\frac{Z''}{2\pi f|Z|^2} \quad (3)$$

$$C'' = \frac{Z'}{2\pi f|Z|^2} \quad (4)$$

$$\phi = -\tan^{-1} \frac{Z'(\omega)}{Z''(\omega)} \quad (5)$$

where f is the frequency,  $|Z|$  stands for the absolute value of impedance, and  $Z'$  and  $Z''$  represent the real and imaginary components of impedance, respectively.

#### 2.6. Construction of asymmetric device

The mass loading of the positive and negative electrodes at different scan rates was determined by the equation (6):

$$C_+V_+m_+ = C_-V_-m_- \quad (6)$$

where  $C_+$  and  $C_-$  are for the gravimetric specific capacitances of the cathode and anode, respectively,  $V_+$  and  $V_-$  decide potential ranges for the cathode and anode, respectively, and  $m_+$  and  $m_-$  are the mass of active electrode materials of the cathode and anode, respectively. The positive electrodes, a porous membrane as a separator, a KCl solution as electrolyte, and the negative electrode were sealed in a plastic bag to assemble the asymmetric device. According to the electrochemical measurement of three electrodes system, the maximum operating voltage is 1.4 V. However, in order to increase the cycle life, 1.2 V was chosen as the operating voltage of the whole system [5].

### 3. Discussion

#### 3.1. Characterization of crystal structure

X-ray diffraction (XRD) was used to analyze the crystallography of as-synthesized. For the positive electrode, after comparing with the standard card, the XRD pattern showed that the high-entropy perovskite powder consists of several phases, which corresponded to the result of former research [16]. The powder was further calcined at 1200 °C for 2 h in air to obtain a single crystal perovskite and the final diffraction patterns of XRD presented the perovskite-type crystal structure of as-synthesized powder as expected. The calcination temperature can be determined by calcining the powder under 1000 °C, 1100 °C, 1200 °C, 1300 °C and 1400 °C and observing the crystal structure at each temperature. The data acquired by the Rietveld refinement of the diffractograms and the average size of crystallites calculated by Scherrer equation are exhibited in Table 1. Rietveld refinement refers to the method that uses the full spectrum of polycrystalline diffraction data. The refined data is then combined with the peak shape function to calculate the spectrum based on the simulated crystal structural model and structural parameters. It also uses the least squares method to adjust the structural parameters and peak shape parameters in order to match the calculated diffraction spectrum with experimental data. A close match would reveal a precise crystal structure information of the. After the comparison with a calculated pattern, the XRD pattern, together with the Rietveld fit, confirms the existence of a single perovskite phase that belongs to Pbnm space group. The XRD patterns of resulting MXene anodes are compared with standard patterns of  $Ti_3C_2T_x$  MXene with a 2D structure to confirm the successful synthesis.

The morphology of electrode materials was studied by scanning electron microscope (SEM), transmission electron microscope (TEM), and high-angle annular dark-field scanning transmission electron microscope (HAADF-STEM). For the high-entropy perovskite, spherical hollow nanospheres particles were shown by SEM, and the photographs are given in Fig. 3a. Besides, TEM was also employed to demonstrate the chemical homogeneity of the positive electrode material, and the pictures are given in Fig. 3b. According to TEM micrograph (Fig. 3c), the perfect crystallinity was proven by the existence of the sharp lattice fringes. Fig 3d exhibits a HAADF-STEM photograph for the sample along the [010] zone axis. From the atomic layers of A-site, which are able to be easily identified from the light transition metal cations of B-site by the average atomic number for sites A and B, a random occupancy of Co, Cr, Fe, Mn, and Ni could be indicated by the similar contrast on the atomic columns at the A-site. For the MXene material, a layered structure with irregular edges was observed from the SEM image (Fig. 4a) rather than multilayered morphology. Furthermore, the single-layered microstructure was also shown by the TEM picture (Fig. 4b).

Energy dispersive spectroscopy (EDS) was used to examine the crystal structure of both positive and negative electrode materials. The qualitative and quantitative analysis of La, Co, Cr, Fe, Mn, and Ni elements in high-entropy perovskite (Fig. 5a) and Ti, O, and F elements in MXene (Fig. 5b) are in good agreement with the above analysis results.

#### 3.2. Electrochemical analysis

The CV study of both the positive and negative electrodes was performed in a three electrodes system with activated carbon films as a counter electrode, Ag/AgCl as the reference electrode, and 3 M KCl as electrolyte at different scan rates (5-100 mV). Perovskite material was recorded at the potential of 0-0.6 V, and the potential window of MXene was -0.8-0 V. The CV curves are presented in Fig. 6a and Fig.

6b, and the rectangular shape indicates the pseudocapacitive mechanism of both electrodes. The change of specific capacitances with scan rate for two materials is exhibited in Fig. 6c. The capacitance of both electrodes decreased while the scan rate increased because of less sufficient time for electrolyte ions to interact with the electrochemically active sites. Furthermore, two equations were introduced to analyze the mechanism during the charge and discharge processes. The first equation that deconvolutes the charge distribution of the semi-definite diffusion process and capacitive process is a power-law relationship between the current  $i$  and the sweep rate  $v$ ,

$$i = av^b \quad (7)$$

where  $a$ -value is a constant, whereas  $b$ -value varies from 0.5 to 1. When the  $b$ -value is close to 0.5, the charge and discharge processes are controlled by capacitive charge processes. When the value is close to 1.0, the processes are controlled by solid state diffusion of electrolyte ions. As the result, via calculating  $b$ -values at different potentials,  $V$  vs  $b$  curves for both positive and negative electrodes were depicted (Fig. 6d and Fig. 6e). The dominant process is determined under different potential ranges. The second formula results in a semi-quantitative analysis of contribution from two kinds of controlled processes. The composition of capacitive and diffusion was set as  $k_1$  and  $k_2$ , which are calculated based on the equation (8)

$$i = k_1v + k_2v^{\frac{1}{2}} \quad (8)$$

By calculating  $k_1$  and  $k_2$  values under different potentials, the relationship between the potential and the exact contribution of capacitive- and diffusion-controlled processes can be established (Fig. 6f and Fig. 6g).

The electrochemical performance of two electrodes was also investigated by GCD in 1 M KCl as an electrolyte. The current density ranges are 1-5  $\text{Ag}^{-1}$  for the positive electrode and 0.5-10  $\text{Ag}^{-1}$  for the negative electrode. From the GCD curves, specific capacitances of different electrodes at different current densities were obtained. The largest specific capacitance for each electrode is at the lowest current density. Furthermore, the cyclic stability and life span of electrodes were studied by GCD cycles over 4000 cycles at a constant current density of 5  $\text{Ag}^{-1}$  for perovskite and 10  $\text{Ag}^{-1}$  for MXene. The long-term stability of the materials can be proved by slight decrease in Coulombic efficiency and minor differences between the 1st and 4000th GCD curves.

EIS was also employed to analyze the electrochemical characterization of positive and negative electrodes. From the Nyquist plots, relative minor transfer resistances and series resistances close to zero appear at the high-frequency region, and the slopes of curves approach  $45^\circ$ , indicating the existence of diffusion-controlled Warburg element. Bode phase plots were also depicted to demonstrate the relationship between phase angle and frequency. The value of phase angle at low frequencies (such as 0.1 Hz and 0.01 Hz) can indicate the pseudocapacitive nature of both high-entropy perovskite and MXene. The high ion transport rates during the electrochemical process can be indicated by the small relaxation time. The relaxation time can be obtained using the equation (9) [16]

$$\tau_0 = \frac{1}{2\pi f_0} \quad (9)$$

where  $f_0$  is the frequency at the phase angle  $-45^\circ$ . Furthermore, the values of real capacitance and imaginary capacitance over frequency were plotted, and the variation of real and imaginary components was clearly observed. In theory, the nature of electrolyte, porosity, and the active mass of electrode material determines the real component together, and the imaginary part of capacitance depends on energy dissipation [17]. Hence, the capacitive behavior of both two electrodes should turn into resistive with an increment of frequency. Besides, the cyclic stabilities were also investigated via 4000 GCD cycles at a constant current density of 5  $\text{Ag}^{-1}$  for perovskite and 10  $\text{Ag}^{-1}$  for MXene. The small decrease in specific capacitance can demonstrate the superior stability of two electrodes.

### 3.3. Influence of elements

To study the influence of each element on the electrochemical properties of high-entropy perovskite, five more samples were synthesized, each without one kind of A-site element (the ratio of other elements was changed to 0.25:0.25:0.25:0.25). Then, the additional samples were tested by using an electrochemical workstation, and the CV curves were depicted in one graph. If one of the samples exhibits a non-box-like profile, the element it lacks should play a decisive role in the pseudocapacitive property of high-entropy perovskite. Other influences can be discovered by comparing the shape of CV curves, and the interesting samples were further investigated by using XRD and TEM to explore the structural change after moving one of the A-site elements.

### 3.4. Structural change

In situ, XRD was employed to investigate the structural change during the charging and discharging process. From the change of the a-, b-, and c-axis lattice parameters, the preferential inserting direction and the storage plane of electrolyte ions can be determined. For the MXene, the change of the c-axis lattice parameter is much larger than that of a- and b-axis parameters. The result matches former research and proves that the electrolyte ions prefer to be inserted in the interlayers. The in-situ characterization of high-entropy perovskite was compared with  $\text{LaMnO}_3$ . The smaller variation of all three lattice parameters can prove the entropy-stabilized conversion mechanism and show the excellent cyclic stability of high-entropy perovskite.

## 4. Conclusion

Lithium-ion batteries are the most popular energy resource for electric devices so far, and supercapacitors used in practical applications remain in its infancy. However, in my view, lithium-ion batteries would only be a transition technology, and supercapacitors should be the ultimate solution for energy conversion and finally change the world. First, the scant metal resource is the dominant limitation for lithium-ion, which is much lower than the reserves of metals that are used in supercapacitors, such as titanium, manganese, and nickel. Nowadays, several leading nations have regarded lithium mines as the most important strategic resource in the new energy era, though the lithium-ion battery is partly used in relatively advanced regions like Europe, North America, and East Asia. It can be expected that a huge demand for lithium elements will exist if all the electric devices in every corner of the world employ lithium-ion batteries as energy sources. Based on this shortage of lithium-ion batteries, supercapacitors exhibit greater power and potential to underpin future requirements of electricity. Second, high power density would prompt more machines to use electricity as an energy supply. A significant amount of energy output of supercapacitors can push larger vehicles like aircraft and rockets. Until now, the electric airplane can only reach a cruise speed of 277 km per hour, which is much lower than the cruise speed of a fuel-driven airplane (more than 800 km per hour). Besides, as automatic driving becomes more and more mature, people seek higher and higher driving speeds, which must have a more powerful energy source. In the future, after human beings can easily overcome gravity, electric rockets should be invented to solve the environmental problems caused by cloudy exhaust gas fumes and toxic unsymmetrical dimethylhydrazine. In this way, if all future vehicles must abandon fuel oil due to climate change and the energy crisis, they must be charged by supercapacitors rather than lithium-ion batteries.

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