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# Efficient Na<sup>+</sup>-storage in a Li<sub>4</sub>Ti<sub>5</sub>O<sub>12</sub> anode to expand the voltage-window for full SIBs of high energy density†

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The stable storage of sodium ions always presents some difficulties for sodium-based dual-ion batteries (S-DIBs), such as the irreversibility of guest-storage and kinetic hindrance in the anode. Based on the low strain volume and stable phase structure, herein, lithium titanate (LTO, Li<sub>4</sub>Ti<sub>5</sub>O<sub>12</sub>) was developed to store sodium ions between the working potential (~0.8 V), which expands the lower plateau over than that of lithium ion storage (~1.55 V) to obtain a high energy density of full batteries. The spinel lithium titanate shows negligible volume change and extremely stable structure under Na<sup>+</sup>-storage, which completely overcomes the shortage problems of the Na<sup>+</sup>-host. Additionally, by the detection of the transfer state of anions and cations in dual-ion batteries, the diffusion coefficient of the sodium ion in the LTO electrode is higher than that of the cathode, which shows that the transport process of sodium ions can meet the kinetic demands of full batteries. Such S-DIBs exhibit a large working voltage of 2.0–4.6 V and stable electrochemical performance over 1280 cycles, which is superior to conventional sodium-based systems, and further exhibit many advantages such as high energy density, environmental friendliness, and low cost.

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## 1 Introduction

Currently, some sodium-storage chemical systems have attracted tremendous attention as next-generation energy storage materials, such as sodium ion batteries (SIBs), sodium-based dual-ion batteries (S-DIBs) and sodium metal batteries (SMBs), which is attributed to the rich availability of the required natural resources and low costs compared to conventional lithium-ion batteries (LIBs). However, the storage host material of sodium ions has always affected the development of sodium-based batteries, owing to the larger diameter of sodium ions leading to slow de/intercalation kinetics and an unstable ion-storage process, whether in cathode or anode materials.<sup>1–4</sup> For the cathodes of sodium storage, dual-ion batteries (DIBs) can ideally avoid this key problem, which is attributed to the special storage mechanism of anion intercalation in the cathode. In DIBs, the layered materials, such as graphite or other layered materials, are usually the anion storage host.

Thus, S-DIBs can solve a part of the important problems faced by sodium-ion storage systems and help them exhibit some indispensable advantages.

Therefore, the key focus of S-DIBs is on anode materials, where there is a stable host structure for storing sodium ions and for realizing fast ion transfer kinetic channels. In this case, many anode materials are prepared to form some practical full S-DIBs, such as metal Na plate,<sup>5,6</sup> Sn metal,<sup>7</sup> soft carbon,<sup>8</sup> and hard carbon,<sup>9</sup> and demonstrate some application potential. However, alloyed materials also retain some problems owing to their highly irreversible reactions, oxygen activity, and low safety, especially metal Na.<sup>10</sup> Additionally, for most anode materials in LIBs, the low kinetic diffusion of sodium ions also leads to poor cycling and power capability.

At the same time, many researchers have proposed a variety of cathode materials for storing sodium ions,<sup>1</sup> such as phosphates, pyrophosphates, fluorosulfates, oxychlorides, and organic compounds, and exhibiting stable electrochemical capability. However, owing to the higher standard potential (~2.71 V vs. SHE as compared to the 3.02 V vs. SHE for lithium) of sodium ions,<sup>11,12</sup> the decreasing voltage window limits the enhancement of the energy density for full batteries. In addition, repetitive phase evolution into the host structure is inevitable during sodium ion intercalation because of the large size of Na<sup>+</sup> (1.02 Å vs. 0.76 Å, ~Li<sup>+</sup>). Thus, it is difficult for its electrochemical performance to achieve the level of similar industrialized LIBs.<sup>13</sup> In order to increase the voltage and cyclic

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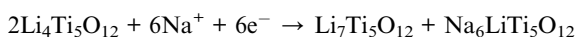
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stability of SIBs, the S-DIBs based on the graphite cathode is better than the traditional SIBs, mainly due to the high voltage range (more than 4 V) and the improved dynamic performance based on anion storage for graphite. For the application of S-DIBs, the key focus has been on matching anode materials for storing sodium ions. Thus, it is necessary to further search for more suitable anode materials to intercalate the sodium ions.

As is well known, lithium titanate (LTO,  $\text{Li}_4\text{Ti}_5\text{O}_{12}$ ) is one of the most promising anode materials in LIBs due to its unique characteristics, such as “zero-strain” in the lattice on the charge/discharge process and the theoretical capacity of  $177 \text{ mA h g}^{-1}$ , resulting in excellent long-life over ten thousand cycles simultaneously.<sup>14,15</sup> Recently, researchers have found that LTO can also store  $\text{Na}^+$  ions by intercalation and deintercalation, same as that of the type of  $\text{Li}^+$ -storage. Sun *et al.* reported that the LTO of  $\text{Na}^+$ -storage can display a theoretical capacity of  $175 \text{ mA h g}^{-1}$  in SIBs.<sup>16,17</sup> DFT calculations can even predict three-phase separation mechanism for the intercalation of  $\text{Na}^+$ , and the coexistence of  $\text{Li}_7\text{Ti}_5\text{O}_{12}$  and  $\text{Na}_6\text{LiTi}_5\text{O}_{12}$ .



After employing the sodium ion as the guest, the LTO shows extremely wide application due to its wider voltage range and higher energy density of the energy storage device.

In theory, we envision that the possibility of LTO is used as a host material to store sodium ions in DIBs. Nevertheless, the intercalated behaviors and its electrochemical properties of sodium ions still remain unclear in full SIBs. In particular, the difference in the structure and the electrochemical differences should be studied after the intercalation of  $\text{Na}^+$  and  $\text{Li}^+$  ions.<sup>18</sup> In this study, the LTO material is employed as the  $\text{Na}^+$ -storage anode for S-DIBs. Through the comparison of electrochemical performance and structural change for the intercalation of both the ions, the LTO anode presents excellent long cycling, especially the obvious increase in the voltage window and energy density in full batteries, as shown in Fig. 1. After analyzing the kinetics of  $\text{Na}^+$ -transport in the phase structure, the high-

performance of S-DIBs can be enabled by the synchronous (de)intercalation capability of  $\text{Na}^+$  in LTO.

## 2 Experimental

### 2.1 Materials and electrodes

For the  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  material, the nanomaterial is used as the target material from the Shenzhen BTR new material. The active anode, carboxymethyl cellulose sodium (CMC, Aladdin M.W. 90 000), styrene butadiene rubber (SBR, Kosyn LATEX KL341, South Korea), and a conductive agent (Super-P, Timical) were mixed in the weight ratio of 7 : 0.5 : 1 : 1.5 in DI water. The resultant slurry was coated onto a copper foil by an automatic coating machine. Also, the loading mass was  $32.5 \text{ g m}^{-2}$  for the  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  electrode. The prepared electrode was dried at  $110^\circ\text{C}$  under vacuum for 6 h to evaporate the water.

Next, 1 M  $\text{LiPF}_6$  or  $\text{NaPF}_6$  was added into the PC/EMC (3 : 7 wt% ratio) solvent, which was used as the electrolyte. They were obtained from JinGuang High-tech (99.99% purity) Co. Ltd.

### 2.2 Electrochemical characterization

For the electrodes in the half-cells and full-batteries, the thickness of the electrode was strictly controlled by the thickness control mold. The proportion of the loading mass for the cathode and anode was taken according to the design of the stoichiometry for the purpose of the experiment. These electrodes were dried at  $120^\circ\text{C}$  under vacuum for 6 h. The half-cells and full-batteries (CR2032) were assembled in a glove box filled with dry Ar atmosphere. The electrolyte in the PC : EMC (3 : 7) solvent was used. The lithium salts had the concentrations of 1 M  $\text{LiPF}_6$  or  $\text{NaPF}_6$ . Electrochemical characterization was conducted using the galvanostatic charge–discharge tests (LAND 2001 CT battery tester). Cyclic voltammetry (CV) curves were collected using the electrochemical workstation with the scanning rate of 0.1, 0.2, 0.4, and  $0.8 \text{ mV s}^{-1}$ . SEM observations were carried out using an XL-30 microscope (Quanta FEG, FEI, PHILIPS). The residual pressure in the Raman and XRD analysis chamber was  $9.3 \times 10^{-7} \text{ Pa}$ . To avoid any contamination from oxygen and water, the cycled electrodes were transferred from the Ar-filled glove box to the chamber using a special air-proof device. XRD studies were carried out using a D8 Advance diffraction system (Bruker, Germany). Raman studies were carried out using the measuring platform (HORIBA XploRA PLUS). In addition, the raw spectra was curve-fitted by nonlinear least squares fittings with a Gauss-Lorentz ratio (80 : 20) using the XPSPEAK41 software. Electrochemical impedance spectroscopy (EIS) was employed using the electrochemical workstation of GAMRY Interface 1000, and the scanning frequency was set in the range of 0.1–100 000 Hz.

## 3 Results and discussion

The prepared-LTO shows nanometer particles and standard crystal structure, as obtained from SEM and XRD in Fig. 2, S1 and S2.† Fig. 2a and b compare the charge–discharge curves

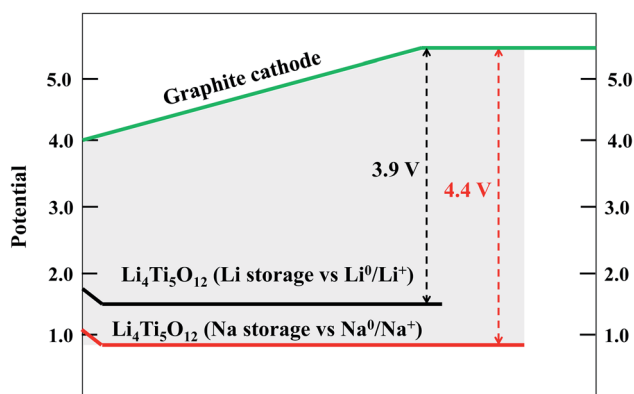


Fig. 1 Voltage profiles of the  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  anode and the graphite cathode in the lithium-based and sodium-based chemical system of dual-ion batteries.

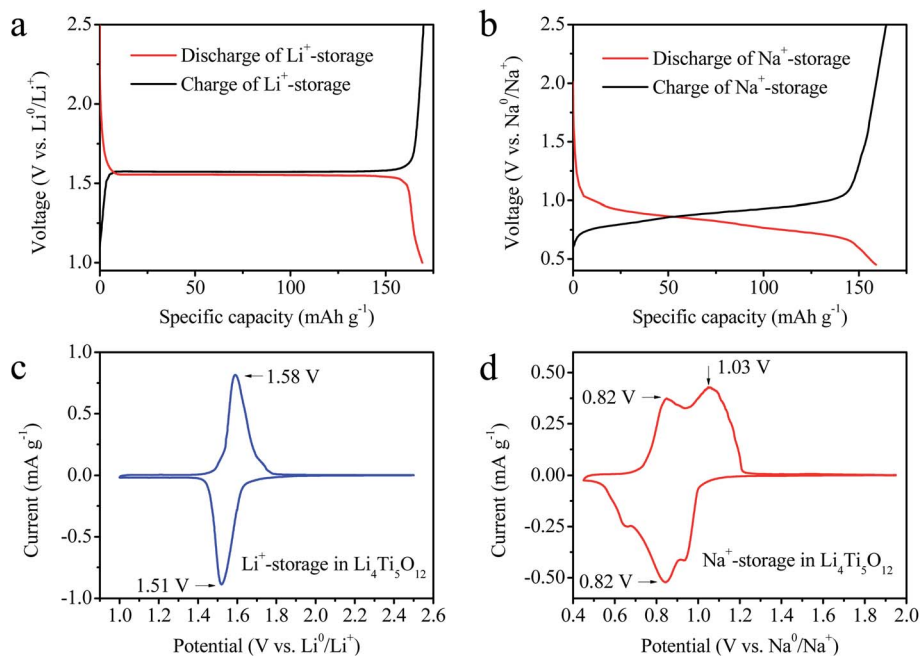


Fig. 2 The charge–discharge curves of the (a) lithium-based and (b) sodium-based  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  half-cell; the cyclic voltammetry curves of the (c) lithium-based and (d) sodium-based  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  half-cell.

during the first-cycle for  $\text{Li}^+$ -storage and  $\text{Na}^+$ -storage in the nanometer LTO electrode. It is known that the potential plateaus at  $\sim 1.55$  V were exhibited for  $\text{Li}^+$ -storage, mainly due to the two-phase transition between the spinel structure (space group  $Fd\bar{3}m$ ) and the rock-salt phase (space group  $Fm\bar{3}m$ ).<sup>2,19</sup> Instead, the LTO electrode for  $\text{Na}^+$ -storage shows a potential drop from open circuit voltage (OCV) to 1 V and a gradual potential decrease from  $\sim 1$  to  $\sim 0.4$  V; thus, the potential plateau of the drop line is different for the curves of  $\text{Li}^+$ -storage. The electrode for  $\text{Na}^+$ -storage demonstrates a specific capacity of  $159.2 \text{ mA h g}^{-1}$ , which is slightly lower than the capacity of  $\text{Li}^+$ -storage ( $\sim 168 \text{ mA h g}^{-1}$ ). Also, the reversible process also shows similar characteristics for charge and discharge. At the same time, the CV curves of  $\text{Li}^+$ -storage and  $\text{Na}^+$ -storage are measured in the potential window of 0.4/2.0 V with a scan rate  $0.1 \text{ mV s}^{-1}$ , as shown in Fig. 2c and d. The sample of  $\text{Li}^+$ -storage exhibits common properties between a cathodic peak at 1.51 V and anodic peak at 1.58 V, which is the same as the (dis)charge curves. Unlike that of  $\text{Li}^+$ -storage, the sample of  $\text{Na}^+$ -storage presents a pair of broad current peaks, and appears at 0.85 V of the cathodic peak and 1.1 V of the anodic peak. The shape of the above peaks verifies the three-phase separation process during the intercalation of  $\text{Na}^+$  ions from the previous studies.<sup>20,21</sup> Some small peaks next to the main peak can also testify the phase transition. In addition, the peak-to-peak splitting for the cathodizing and anodizing of the  $\text{Na}^+$ -storage is obviously larger compared to that of the  $\text{Li}^+$ -storage. This splitting is attributed to the increasing kinetic impedance for  $\text{Na}^+$  in the nanocrystalline phase, which is consistent with the previous reports.<sup>16,22</sup> Chronopotentiometric measurement confirms that the diffusion and intercalation of  $\text{Na}^+$  into the nanomaterials maybe present some problems.

In order to compare the kinetic behavior of both kinds of ions in the LTO phase, the galvanostatic intermittent titration technique (GITT) is applied during the charge and discharge process.<sup>23</sup> Fig. 3a and b describe the curves of GITT under discharge–charge after pre-cycling. It can be seen from the curves that the voltage trends are different but the change trends are basically corresponding to the charge–discharge curves in Fig. 2a and b under the near-equilibrium state. The diffusion coefficients of the ions are calculated under different state of charge (SOC) from the GITT curves, combined with Fick's second law.<sup>24,25</sup>

$$D = \frac{4}{\pi} \left( \frac{m_B V_M}{M_B S} \right)^2 \left( \frac{\Delta E_S}{\tau} / \left( \frac{dE_\tau}{d\sqrt{\tau}} \right) \right)^2 \left( t \ll \frac{L^2}{D} \right)$$

here,  $m_B$ ,  $M_B$ ,  $V_M$ , and  $S$  are defined as the molar weight, LTO mass, molecular volume, and geometric area of the materials, respectively. Also,  $\tau$ ,  $\Delta E_S$ , and  $E_\tau$  are the duration time of the current pulse, voltage change at the steady state, and transient voltage during the titration process.<sup>26</sup> In the GITT experiment, the voltage window of the LTO anode is selected at 1–2.5 V for  $\text{Li}^+$ -storage and 0.25–2.25 V for  $\text{Na}^+$ -storage by a series of intermittent current ( $100 \text{ mA g}^{-1}$ ) for 30 min and then kept still at the open circuit for 10 h. The calculated data of the diffusion coefficient ( $D_s$ ) are demonstrated in Fig. 3c and d. More importantly, the  $D_s$  of  $\text{Na}^+$  in the LTO ( $\sim 10^{-12}$  to  $10^{-15} \text{ cm}^2 \text{ s}^{-1}$ ) is slightly lower than that of  $\text{Li}^+$  ( $\sim 10^{-12}$  to  $10^{-16} \text{ cm}^2 \text{ s}^{-1}$ ), and the value depends on the state of charge (SOC). For  $\text{Na}^+$ -storage, the  $D_s$  is obviously low under the state of poor- $\text{Na}^+$  and rich- $\text{Na}^+$ , in other words, the materials as the phase of  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  and  $\text{LiNa}_3\text{Ti}_5\text{O}_{12}$ . At the same time, it also reflects that the diffusion impedance of  $\text{Na}^+$ -storage is higher than that of  $\text{Li}^+$ -storage,

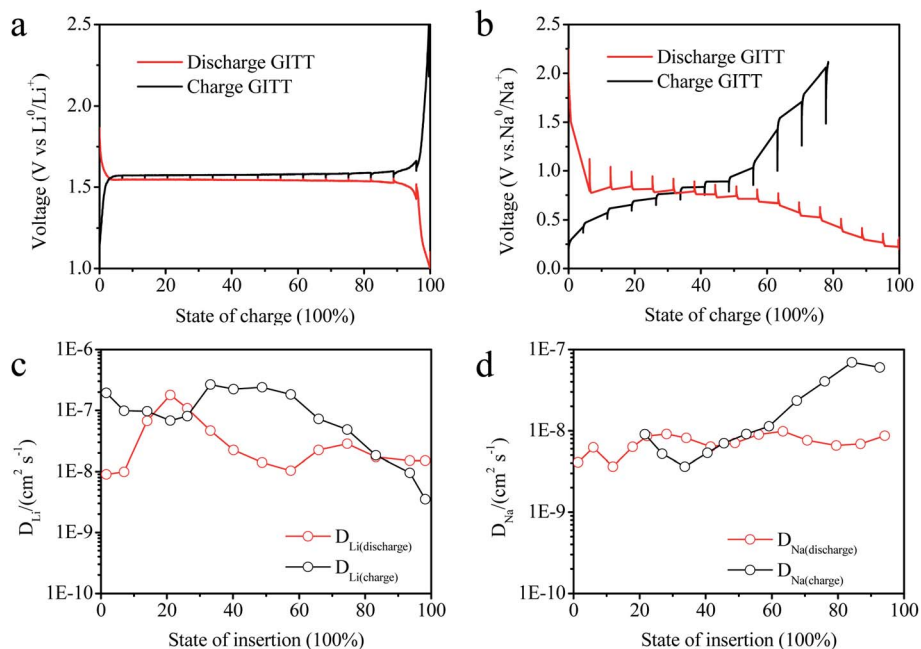


Fig. 3 The GITT curves and ion diffusion coefficient of the (a), (c) lithium-based and (b), (d) sodium-based half-cell.

which leads to the larger splitting voltage and low specific capacity.

Fig. 4a displays the electrochemical cycling curves for  $\text{Na}^+$  in the half-cell ( $\text{LTO}|\text{Na}$ ) under the rate of 0.5C. In the first cycles, the battery shows the capacity of  $166.98 \text{ mA h g}^{-1}$  for  $\text{Na}^+$ -insertion and capacity of  $163.53 \text{ mA h g}^{-1}$  for  $\text{Na}^+$ -extraction, which approached the theoretical capacity of LTO. It depicts the stable phase structure used to store  $\text{Na}^+$ . In the following cycles, the specific capacity of LTO remains above  $150 \text{ mA h g}^{-1}$  in the

first 500 cycles, as shown in Fig. 4b. At the same time, the voltage plateau shows obvious changes for the decrease in the discharge and increase in the charge process. This result can be considered due to the increase in the kinetics polarization and the mass transfer resistance of  $\text{Na}^+$  in the LTO phase. Owing to the larger radius of  $\text{Na}^+$ , the diffusion problem of the interface of the electrode and the electrolyte is still the most possible reason, in comparison to the transmission kinetics in the solid material.

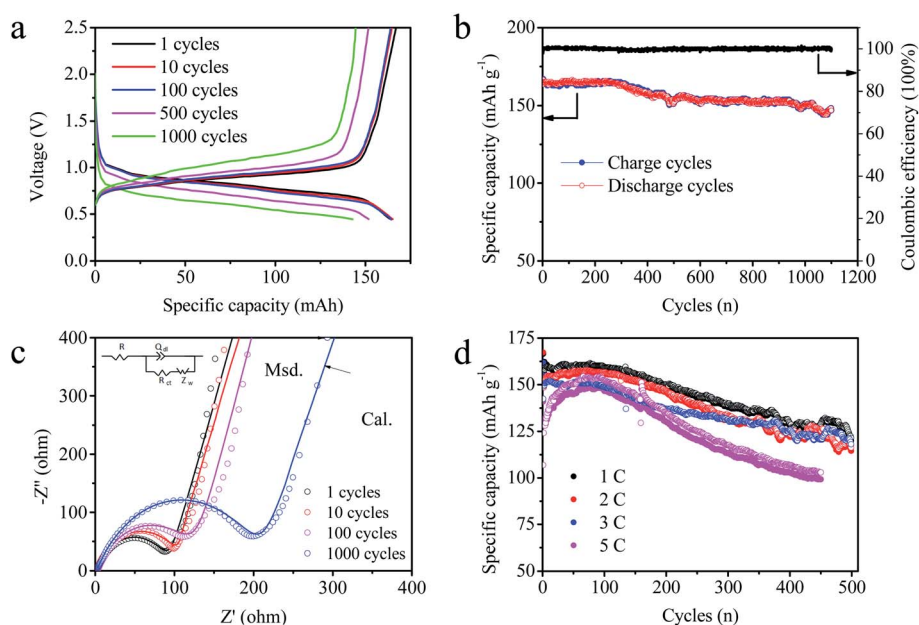


Fig. 4 (a) Charge–discharge curves and (b) life cycling of the  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  half-cell, (c) the EIS curves and (d) rate performance.

Electrochemical impedance spectroscopy (EIS) was employed to study the impedance after the (de)intercalation of  $\text{Na}^+$  under different cycles (1, 10, 100, and 1000 cycles), as shown in Fig. 4c. The curves exhibit a semicircle at high-middle frequency and a diagonal line at low frequency. Through the simulation of the equivalent circuit (the inset of Fig. 4c), the fitting curves are highly consistent with the real impedance spectrum. After analysis, the part of the semicircle is considered to be the charge transfer resistance ( $R_{\text{ct}}$ ) at the interface related to the alloy of poor-sodium for LTO particles.<sup>27,28</sup> It can be seen that the  $R_{\text{ct}}$  of the electrode slightly increased from 95.6 Ohm to 100.2 Ohm at 10 cycles but increased to 122.2 Ohm at 100 cycles and further reached 205 Ohm after 1000 cycles, which indicated that the resistance gradually increased from the diffusion capability at the solid-liquid interface.

The rate properties during high current density can reflect the capability of diffusion and intercalation for  $\text{Na}^+$  in LTO materials. Fig. 4d presents the cycling curves at the rate of 1C to 5C. In the first cycle, the cell respectively provides the capacities of 164.8, 161.3, 157.2, and 104.3  $\text{mA h g}^{-1}$  at four kinds of rates, which decreases according to the increase in the rates. It indicates that  $\text{Na}^+$  can quickly transport in nanometer materials under the intercalation reaction process of LTO. For continuous cycling, it can be seen that the performance is relatively stable at 1–3 C, and is slightly worse at 5C but the capacity unexpectedly gradually restored after the first 50 cycles. After 500 cycles, respectively, the capacities were decreased to 120.0, 116.5, 112.0, and 99.3  $\text{mA h g}^{-1}$ , and the attenuation rates were 72.8%, 72.1%, 71.2%, and 66.4% (calculated based on the highest specific capacity at the initial 5C rate). Despite such a relatively

large capacity drop at the rate of 5C, its capacity remains at a high level in rate compared to the graphite cathode for DIBs.

Very recently, the capability of fast transport for  $\text{Li}^+$  in the two-phase reaction was revealed, which are attributed to the kinetics pathway along a two-phase boundary in the presence of metastable intermediates.<sup>29</sup> For the behavior of  $\text{Na}^+$  in LTO, we also estimated that  $\text{Na}^+$  also reaches intercalation in a similar manner of transport. However, owing to the larger radius of  $\text{Na}^+$  ( $\sim 101 \text{ \AA}$ ) than that of  $\text{Li}^+$  ( $\sim 60 \text{ \AA}$ ), the structural changes may present some differences from  $\text{Li}^+$  after the intercalation of  $\text{Na}^+$  into the LTO phase.<sup>30</sup> Fig. 5a shows the comparison of the Raman spectra of the LTO phase before and after the intercalation of  $\text{Li}^+$  and  $\text{Na}^+$  ions. The Raman curve of the fresh electrode (black line) exhibits three main characteristic peaks at  $234 \text{ cm}^{-1}$ ,  $424 \text{ cm}^{-1}$ , and  $674 \text{ cm}^{-1}$ , which are assigned to the transport energy of F1g, Eg, and A1g, respectively.<sup>31</sup> For the LTO of the  $\text{Li}^+$ -storage (red line), the curves show obvious differences from the original characteristic peaks ( $\sim$ fresh electrode), which reflects the weakening of F 1g and red-shifting to a lower wavenumber of Eg and A1g, such as Eg (from  $424 \text{ cm}^{-1}$  to  $410 \text{ cm}^{-1}$ ) and A1g (from  $674 \text{ cm}^{-1}$  to  $622 \text{ cm}^{-1}$ ). At the same time, an additional peak at the position of  $167 \text{ cm}^{-1}$  is attributed to orthorhombic titanate,  $\text{Li}_{0.5}\text{TiO}_2$  (space group *Imma*),<sup>32</sup> which is mainly due to the structure formed by the Li-intercalated tetragonal anatase  $\text{TiO}_2$  (space group *I4<sub>1</sub>/amd*) at the level of full Li-intercalation ( $x \approx 0.5$ ).<sup>33</sup> However, the Raman spectrum of  $\text{Na}^+$ -storage (blue line) shows some clear changes occurring within the above regions. The corresponding intensity at  $167 \text{ cm}^{-1}$  became sharper, which should be due to the intercalation of  $\text{Na}^+$ , inducing the rearrangement of Li atoms in the original LTO phase into the orthorhombic titanate

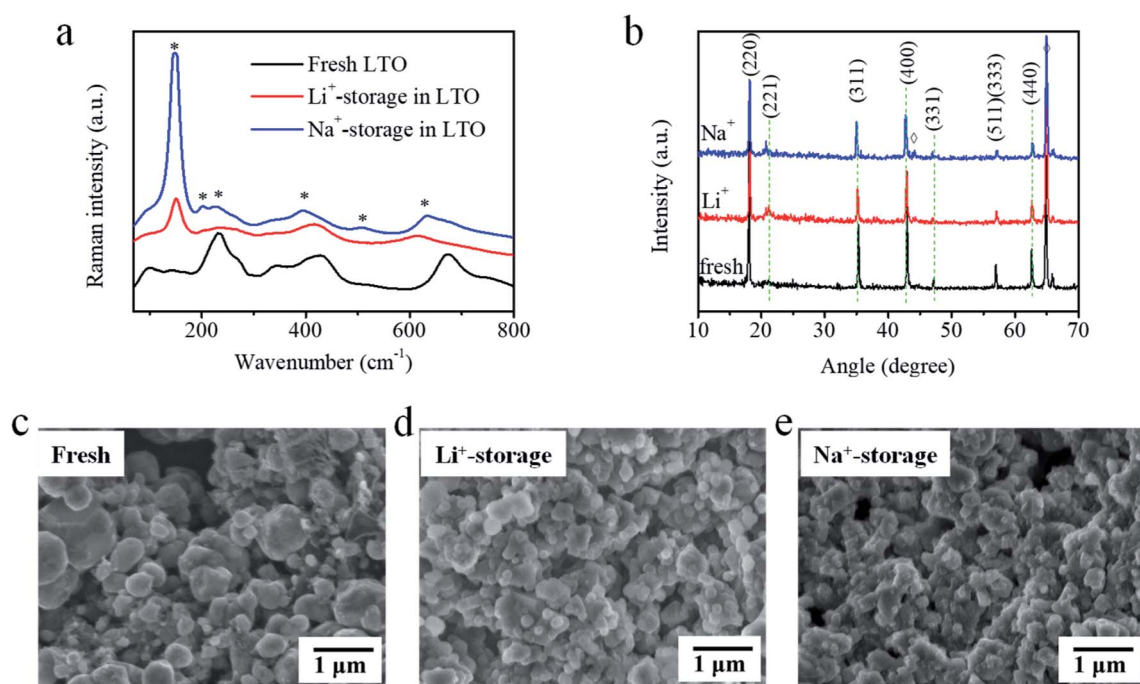


Fig. 5 Comparison of (a) Raman, (b) XRD curves, and (c)–(e) SEM images of  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  electrodes before and after the intercalation of lithium ions and sodium ions.

( $\sim\text{Li}_{0.5}\text{TiO}_2$ ).<sup>20</sup> In addition, a subtle peak appeared at  $180\text{ cm}^{-1}$  to the right of  $167\text{ cm}^{-1}$ , and it may also be related to the formation of tetragonal anatase,  $\text{TiO}_2$ .<sup>33</sup> Also, there is still a weak characteristic peak ( $\sim\text{F1g}$ ) at the original position of  $229\text{ cm}^{-1}$ .<sup>34</sup> At the same time, for the red-shifted Eg and A1g peaks, the region of Eg is shifted to lower wavenumber (red shift), which appeared at  $390\text{ cm}^{-1}$ . The Eg peak represents the tensile vibration mode of Li–O in tetrahedra  $\text{LiO}_4$ ; the transport energy of Li–O shows weakening after the intercalation of  $\text{Na}^+$  replaces  $\text{Li}^+$  in phase.<sup>32</sup> In addition, the A1g peak exhibits stronger intensity without the shifting of position, which indicates the tensile motion mode of Ti–O in octahedra  $\text{TiO}_6$ . In addition, a subtle but clear peak appeared at the position of  $526\text{ cm}^{-1}$ , which is also attributed to the new substance formed by  $\text{Na}^+$  and  $\text{TiO}_2$ . Therefore, Raman spectroscopy confirms that the impact on LTO is stronger for  $\text{Na}^+$ -storage compared to  $\text{Li}^+$ -storage owing to the larger radius.

At the same time, X-ray diffraction was conducted to further compare the structural differences in the process of  $\text{Li}^+$ -storage and  $\text{Na}^+$ -storage, as illustrated in Fig. 5b. The patterns of fresh-LTO show main peaks appearing at  $18.4^\circ$ ,  $35.2^\circ$ ,  $42.7^\circ$ , and  $62.9^\circ$ , which are attributed to the peaks of (220), (311), (400), and (440), respectively.<sup>35,36</sup> For the rich- $\text{Li}^+$  and  $\text{Na}^+$  electrodes, the characteristic peak is almost the same as that of the fresh electrode. Nonetheless, subtle but clear changes occurred within the side region of the peaks. Interestingly, the diffraction peaks of (221) and (311) at  $20.8^\circ$  and  $41.9^\circ$  for  $\text{Na}^+$ -storage are shifted on the basis of  $\text{Li}^+$ -storage.<sup>16</sup> Also, the intensity of the peaks of (331) and (440) at  $52.1^\circ$  and  $62.9^\circ$  becomes weaker.<sup>35,36</sup> As we know that owing to the LTO serving as a “zero strain” anode, the characteristic peaks remain relatively stable but

some weak changes still exist, which indicates that the intercalation of  $\text{Na}^+$  also bears some influences from the LTO phase.<sup>22</sup> Moreover, Fig. 5c–e displays the morphology of the LTO electrode before and after ion-storage. Combined with the XRD pattern, it can be seen from the SEM results that the shape and distribution of the LTO electrode show no obvious changes after the intercalation of  $\text{Na}^+$ . Also, the structural characteristics indicate that this material can achieve the stable intercalation–deintercalation of  $\text{Na}^+$ . Thus, the above results show that the  $\text{Na}^+$ -storage of LTO materials can increase the voltage window and solve the scarcity of the host for  $\text{Na}^+$  guest, although the diffusion properties of  $\text{Na}^+$  have slight insufficiency compared to  $\text{Li}^+$  storage.<sup>37</sup>

In DIBs, the anions and cations from the electrolyte can be simultaneously intercalated into the anode and cathode electrodes; therefore, the properties of diffusion in both the electrodes for anions and cations play the same important role. To improve the electrochemical performance of DIBs, it is necessary to analyze the diffusion kinetics of the ions in both the materials. Fig. 6a shows that the GITT curves of the layered graphite cathode during charging and discharging (anionic intercalation and deintercalation) process is measured, and that the voltage is the range of 3.5–5 V. According to Fick's second law, the anion diffusion coefficients ( $D_{\text{PF}_6^-}$ ) with different insertion ratios are calculated, as shown in Fig. 6b. At the same time, the diffusion coefficient of sodium ions ( $D_{\text{Na}^+}$ ) in the LTO is also compared in the figure. It can be seen from these curves that  $D_{\text{Na}^+}$  is concentrated in the range of  $10^{-8}$  to  $10^{-9}\text{ cm}^2\text{ s}^{-1}$ , and the maximum value can reach  $10^{-7}\text{ cm}^2\text{ s}^{-1}$  when sodium is fully sodiated. Instead, the  $D_{\text{PF}_6^-}$  for intercalation and deintercalation is distributed over a wider range with different intercalation states, which are  $10^{-11}$  to  $10^{-9}\text{ cm}^2\text{ s}^{-1}$ , and

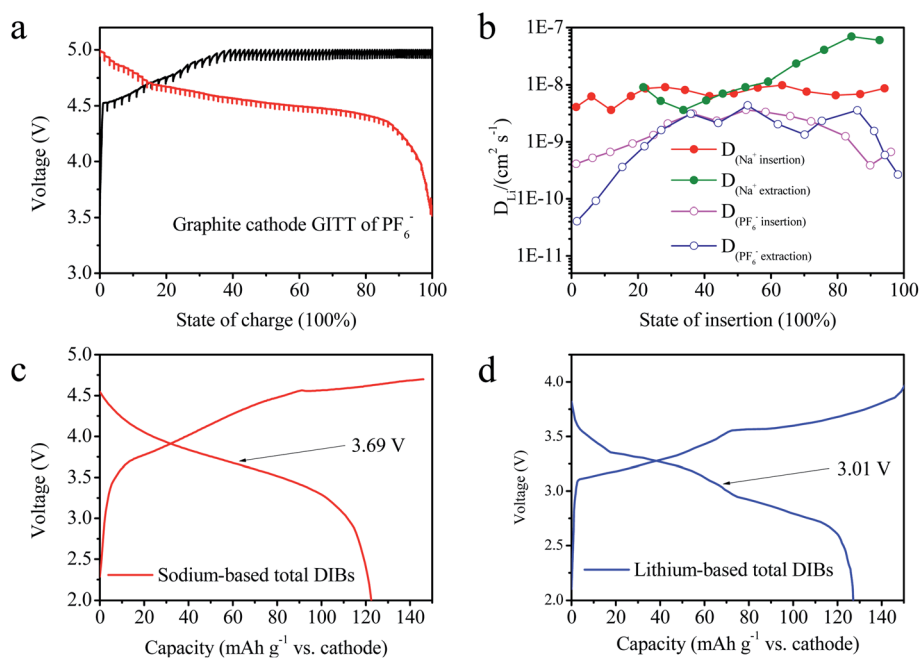


Fig. 6 (a) The GITT curves of the graphite cathode for the  $\text{PF}_6^-$  intercalation. (b)  $D$  of  $\text{Na}^+$  and  $\text{PF}_6^-$  ions calculated from the GITT curves as a function of the voltage for the  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  anode and graphite cathode, respectively. Charge–discharge curves of sodium-based (c) and lithium-based (d) for total DIBs.

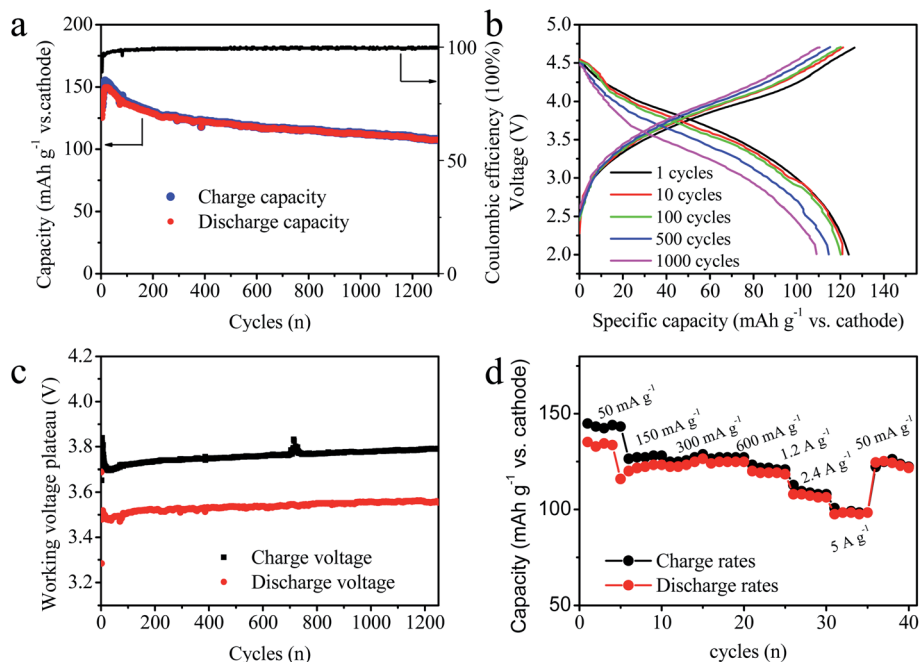


Fig. 7 (a) The cycling performance of full S-DIBs, (b) the charge–discharge curves at different cycles, and (c) the corresponding voltage plateaus at the middle capacity. (d) The rate performance at current density in the range of  $50 \text{ mA h}^{-1}$  to  $5000 \text{ mA g}^{-1}$ .

slightly lower in poor- $\text{PF}_6^-$  and rich- $\text{PF}_6^-$ . Then, the value of  $D_{\text{Na}^+}$  is higher than that of  $D_{\text{PF}_6^-}$  in graphite in the full batteries. Therefore, although the  $D_{\text{Na}^+}$  is lower than that of lithium ions (Fig. 3), the electrochemical performance of the sodium-based system is not limited when LTO and graphite are assembled into the system.

Fig. 6c demonstrates the charge–discharge curves of full DIBs (LTO|graphite), and the voltage is in the range of 2–4.6 V. With the excessive coating mass of the LTO anode, the full battery shows a charge capacity of  $142 \text{ mA h g}^{-1}$  and discharge capacity of  $123 \text{ mA h g}^{-1}$ . This capacity reflects a nominal capacity of the graphite cathode owing to the higher loading mass of the anode electrode. At the same time, the full battery also shows the voltage plateau of 3.68 V. In comparison, the Li-based full-batteries (Fig. 6d) exhibit a voltage platform of 3.02 V in the range of 4–2 V, which shows a relatively low energy density. Such a system has also been reported in the previous literature (Table S1†) but the performance of lithium titanate has reached that of industry materials in this article.

For long cycles in Fig. 7a, the full battery shows the capacity of  $122 \text{ mA h g}^{-1}$  in the initial stage, which steadily increased in the following cycles, which may be due to the gradual activation process of the anode that is initially caused by the difference in the specific capacities of the cathode and the anode. After 1200 cycles, the cell capacity remains stable at  $106 \text{ mA h g}^{-1}$ . By comparing the charge–discharge process, the (dis)charge capacity shows similar changing trends in cycling in Fig. 7b. However, the voltage plateau in the discharge curve still shows a certain drop, and the corresponding charging plateau increased slightly in Fig. 7c. For rate cycling, it can be seen that the capacity of the full battery remains relatively stable under different discharge current densities ( $50, 150, 300, 600, 1200,$

$2400,$  and  $5000 \text{ mA h g}^{-1}$ ) in Fig. 7d. By testing the electrochemical performance, it proved that such a chemical system has great application potential, which cannot only overcome the shortage of sodium ion batteries in materials but also achieves higher energy density.

## 4 Conclusion

As an anode material with the structure of “zero strain”, lithium titanate can maintain a relatively stable crystalline phase after intercalation by  $\text{Na}^+$  instead of  $\text{Li}^+$ .  $\text{Na}^+$ -storage can decrease the average voltage (vs.  $\text{Li}/\text{Li}^+$ ) of the anode to achieve the high working voltage in full DIBs (2–4.5 V). Comparing the diffusion properties of  $\text{Na}^+$  and  $\text{PF}_6^-$  in the host materials, the transport rate of  $\text{Na}^+$  in LTO is proved to meet the kinetic process between the anode and the cathode electrodes in assembled full batteries. Excellent electrochemical and stable storage performance reflects the application advantages of the sodium-guest energy storage system. These S-DIBs with the LTO anode can significantly enhance the energy density of the full batteries to trigger the industrial studies of  $\text{Na}^+$ -storage host materials.

## Conflicts of interest

There are no conflicts to declare.

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