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# Enhanced capacitive properties of all-metal-oxide-nanoparticle-based asymmetric supercapacitors†

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The major problem of transition metal oxide (TMO)-based supercapacitors is their low specific energy ( $E_{sp}$ ) due to the poor electrical conductivity of the TMO electrodes and narrow operating voltage window. To solve these limitations simultaneously, we propose asymmetric supercapacitors (ASCs) consisting of two composite TMO electrodes working in different potential ranges. Titanium dioxide ( $\text{TiO}_2$ ) nanoparticle (NP)-incorporated iron oxide ( $\text{Fe}_2\text{O}_3$ ) and manganese oxide ( $\text{MnO}_2$ ) NPs were used as electrode materials covering the negative and positive potential window, respectively. The specific capacitance ( $C_{sp}$ ) of this asymmetric  $\text{TiO}_2\text{-Fe}_2\text{O}_3\|\text{TiO}_2\text{-MnO}_2$  supercapacitor is comparable to that of the symmetric  $\text{TiO}_2\text{-MnO}_2\|\text{TiO}_2\text{-MnO}_2$  supercapacitor. However, the ASC can operate over a doubly extended voltage range, which resulted in a significant enhancement in the specific energy of the device. The  $E_{sp}$  value of the ASC at a specific power of  $1000 \text{ W kg}^{-1}$  is  $48.6 \text{ W h kg}^{-1}$ , which is 34.1 and 8.1 times, respectively, larger than that of the two symmetric devices.

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## Introduction

Pseudocapacitors have attracted growing attention due to their superior specific capacitance ( $C_{sp}$ ) compared to other types of supercapacitors, mainly electrical double layer capacitors (EDLCs).<sup>1–3</sup> The high  $C_{sp}$  values of pseudocapacitors are attributed to the faradaic redox reactions of the electrode materials for storing charges while the EDLCs use only non-faradaic charge storage on the electrode surface.<sup>3,4</sup> Especially, transition metal oxides (TMOs) have been widely investigated as an electrode material for pseudocapacitors due to their high theoretical  $C_{sp}$  values and variant redox characteristics.<sup>5–7</sup>

However, the major limitation of the TMO-based pseudocapacitors is their low energy density due to the intrinsically narrow redox potential of the TMOs because the energy density ( $E$ ) is proportional to the square of the operating voltage window ( $\Delta V$ ),  $E = C_{sp}(\Delta V)^2/2$ .<sup>8,9</sup> To solve this problem, an asymmetric supercapacitor (ASC) has been studied to widen the voltage window by integrating two electrodes with different working potentials. Normally, TMOs with a positive working potential have been used as a positive electrode, while carbon materials such as graphene,<sup>9,10</sup> activated carbon,<sup>11,12</sup> and carbon

nanotube<sup>13</sup> have been used as a negative electrode. However, the relatively low specific capacitance of the carbon-based electrode still hampers the further enhancement of the energy density. Thus, ASCs comprised of two TMO-based electrodes with different redox potentials are a promising candidate. Another challenging fact is that most TMOs have poor electrical conductivity, which leads to a low rate capability and a rapid decrease in the electrode thickness.<sup>14–16</sup> To overcome this problem, various electrode nanostructures have been proposed to increase the contact between the electrode and electrolyte.<sup>16–19</sup> Although nanostructured electrodes have improved the capacitive characteristics to some extent, most fabrication techniques are still expensive and complicated for practical use. In contrast, a much simpler, low-cost preparation for a variety of TMO nanoparticles (NPs) has been well established, and hence the TMO NPs are promising materials for nanostructured supercapacitor electrodes. However, very limited studies have been reported on all TMO-NPs-based ASCs; therefore, the preparation and capacitive property of such devices are of significant interest from both a fundamental and technological perspective.

In this study, we developed the ASC consisting of manganese oxide ( $\text{MnO}_2$ ) and iron(III) oxide ( $\text{Fe}_2\text{O}_3$ ) NPs-based electrodes. These two TMOs are low-cost, non-toxic and easily obtained from naturally abundant minerals. Furthermore, these TMO-based electrodes work at different potentials, and hence their combination is expected to widen the voltage window of the ASC.<sup>20–22</sup> The working potentials of the  $\text{MnO}_2$  and  $\text{Fe}_2\text{O}_3$  electrodes were reported as 0.0–1.0 V and –1.1–0.2 V, respectively.<sup>15,23–26</sup> A small amount of titanium oxide ( $\text{TiO}_2$ ) NPs was also incorporated into the  $\text{MnO}_2$  and  $\text{Fe}_2\text{O}_3$  electrodes for

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a synergetic improvement of the electrode performance. The incorporation of the  $\text{TiO}_2$  NPs was expected to improve the charge transport characteristics of the TMO electrodes because the electrical conductivity of  $\text{TiO}_2$  ( $10^{-5}$  to  $10^{-2} \text{ S cm}^{-1}$ ) is higher than that of  $\text{MnO}_2$  ( $10^{-6}$  to  $10^{-5} \text{ S cm}^{-1}$ ) and  $\text{Fe}_2\text{O}_3$  ( $10^{-9}$  to  $10^{-7} \text{ S cm}^{-1}$ ).<sup>27,28</sup> In addition, the  $\text{TiO}_2$  NPs are stable, inexpensive and readily available. The all-TMO-NPs-based ASC with an architecture of  $\text{TiO}_2\text{-Fe}_2\text{O}_3\|\text{TiO}_2\text{-MnO}_2$  could operate over a significantly extended voltage range of 2.0 V, and hence, its specific energy was approximately 34.1 and 8.1 times larger than those of the  $\text{TiO}_2\text{-Fe}_2\text{O}_3\|\text{TiO}_2\text{-Fe}_2\text{O}_3$  and  $\text{TiO}_2\text{-MnO}_2\|\text{TiO}_2\text{-MnO}_2$  symmetric supercapacitors, respectively. Other capacitive properties of the  $\text{Fe}_2\text{O}_3\|\text{MnO}_2$ -based ASC such as the voltammetric response and cycle life were also investigated.

## Experimental

First, the synthetic process for the  $\text{MnO}_2$  and  $\text{Fe}_2\text{O}_3$  NPs from their precursors, potassium permanganate ( $\text{KMnO}_4$ ) and iron(III) nitrate ( $\text{Fe}(\text{NO}_3)_3$ ), respectively, was described elsewhere.<sup>29</sup> During the synthesis of the NPs, commercially available  $\text{TiO}_2$  NPs (anatase, Dysol) with an average diameter of 10 nm were added to the synthetic reactor for their incorporation. The amount of  $\text{TiO}_2$  NPs used was one-tenth the weight of each precursor, which corresponds to 15 wt% for the  $\text{TiO}_2\text{-MnO}_2$  composite NPs and 13 wt% for the  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  composite NPs, assuming that the reaction proceeded completely. The  $\text{TiO}_2\text{-MnO}_2$  electrode was prepared by dipping a nickel foam into a slurry containing  $\text{TiO}_2\text{-MnO}_2$  NPs as an active material, super-P as a conductive additive, and polytetrafluoroethylene (PTFE, Aldrich) as a binder with a weight ratio of 8 : 1 : 1. The  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  electrode was prepared in a similar manner except that a fluorine-doped tin oxide (FTO) substrate was used instead of Ni foam as a current collector. The loading mass of each electrode was measured using a microbalance. The ASC was prepared by stacking the  $\text{TiO}_2\text{-MnO}_2$  electrode and  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  electrode with a membrane filter paper as a separator in between.

The morphology and crystalline structure of the synthesized NPs were characterized by field emission scanning electron microscopy (FE-SEM, JSM-7410F, JEOL Ltd.), transmission electron microscopy (TEM, JEM-2100F, JEOL Ltd.), and X-ray diffraction (XRD, Rigaku D/Max2500). The specific surface area of the NPs were also estimated using a Brunauer–Emmett–Teller (BET) surface area analyser (QuadraSorb Station 2, Quantachrome Instrument). The capacitive properties of the electrodes and ASCs were evaluated using a cyclic voltammeter (ZIVE SP2, WonATech) in a 1.0 M aqueous  $\text{Na}_2\text{SO}_4$  electrolyte solution. While a two electrode system was used for the symmetric and asymmetric full-cell capacitors, a three electrode system, *i.e.* the TMO electrode as a working electrode, a platinum plate as a counter electrode, and  $\text{Ag}/\text{AgCl}$  (in 3 M KCl) as a reference electrode, was used to evaluate the individual electrode.

## Results and discussion

The morphologies of the  $\text{TiO}_2$ -NPs-embedded  $\text{Fe}_2\text{O}_3$  and  $\text{MnO}_2$  NPs were characterized by FE-SEM (Fig. 1a and b). Uniform,

spherical particles with tens of nanometers in size were clearly observed. The elemental SEM-mapping results for the Ti atoms shown in the inset of the figures indicated that the  $\text{TiO}_2$  NPs were well and uniformly dispersed. The Ti/Fe and Ti/Mn atomic ratios determined from the SEM-mapping analyses were equivalent to the mole fraction of  $\text{TiO}_2$  used, indicating a stoichiometric embedment of the  $\text{TiO}_2$  NPs. The crystallinities of the  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  and  $\text{TiO}_2\text{-MnO}_2$  composite NPs were characterized by XRD measurements. While clear diffraction patterns corresponding to the hematite  $\alpha\text{-Fe}_2\text{O}_3$  phase<sup>30</sup> for the  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  NPs were observed (Fig. 1c), the broader peaks of the  $\text{TiO}_2\text{-MnO}_2$  NPs (Fig. 1d) indicated typical amorphous characteristic of the  $\text{MnO}_2$  NPs.<sup>31–33</sup> Additional diffraction peaks corresponding to the  $\text{TiO}_2$  anatase phase were also observed for both composite NPs. More close morphology of the synthesized TMO NPs were observed by TEM (Fig. S2†). In the case of  $\text{Fe}_2\text{O}_3$  NPs, the clear lattice fringe in the TEM image and spots and rings in the selected area electron diffraction (SAED) pattern indicated the polycrystalline characteristics. In contrast, for the  $\text{MnO}_2$  NPs, the fringes and SAED spots were hardly observed, indicating relatively amorphous characteristics, consistent with the XRD results.

Fig. 2a shows the cyclic voltammogram (CV) measured using a three-electrode system at a scan rate of  $30 \text{ mV s}^{-1}$  for the  $\text{Fe}_2\text{O}_3$  (negative voltage range) and  $\text{MnO}_2$  (positive voltage range) half-cell electrodes with and without  $\text{TiO}_2$  incorporation. The specific capacitance,  $C_{\text{sp}}$ , of the electrodes was calculated by the following equation;

$$C_{\text{sp}} = \frac{I}{m(dV/dt)} \quad (1)$$

where  $I$  (A) is the average current,  $m$  (g) is the deposit weight, and  $dV/dt$  ( $\text{mV s}^{-1}$ ) is the scan rate.<sup>34</sup> The area of the CV contour, indicative of the specific capacitance, of the  $\text{TiO}_2\text{-MnO}_2$  electrode is significantly larger than that of the  $\text{TiO}_2$ -free  $\text{MnO}_2$  electrode, while the areas of the  $\text{Fe}_2\text{O}_3$  electrode are little varied.

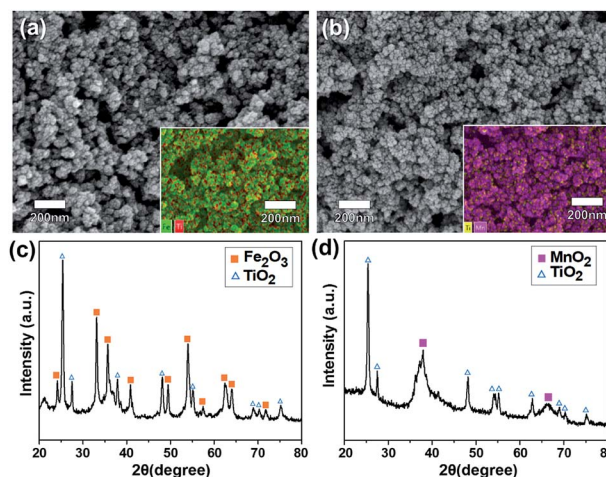


Fig. 1 FE-SEM images of (a)  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  and (b)  $\text{TiO}_2\text{-MnO}_2$  NPs, and XRD patterns of (c)  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  and (d)  $\text{TiO}_2\text{-MnO}_2$  NPs. The inset SEM-mapping images for Ti atoms in (a) and (b) show uniform dispersion of the  $\text{TiO}_2$  NPs.



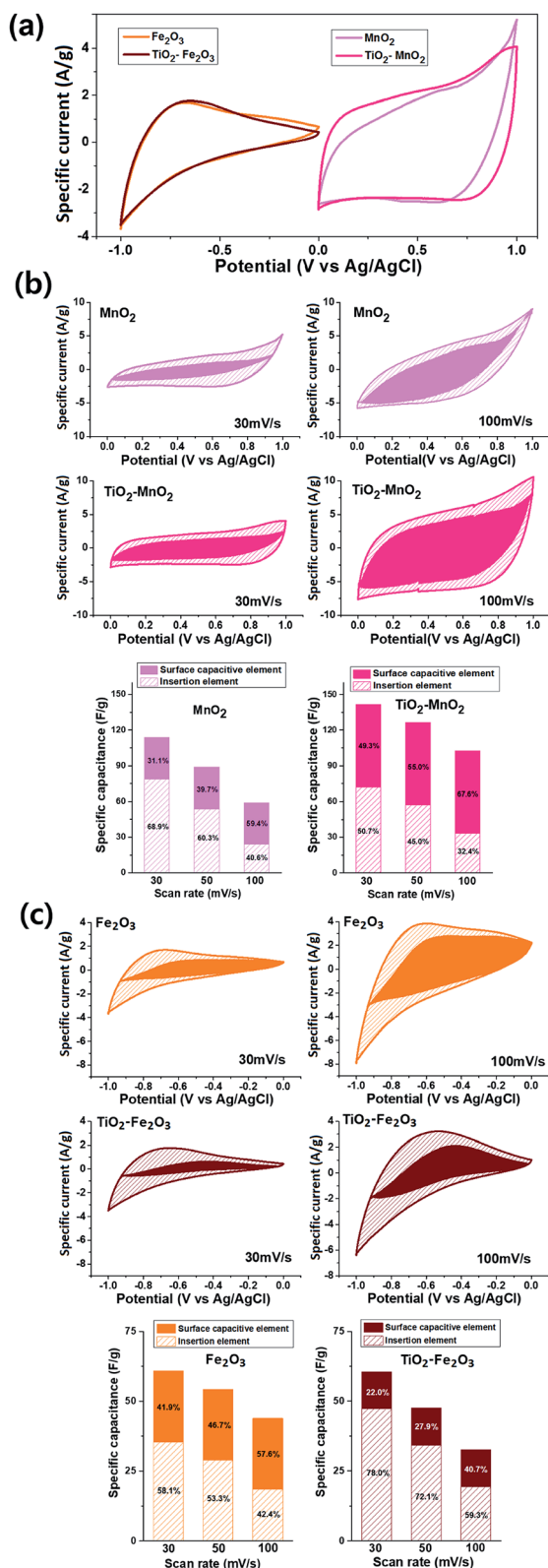


Fig. 2 Cyclic voltammograms of the  $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2\text{-Fe}_2\text{O}_3$ ,  $\text{MnO}_2$ ,  $\text{TiO}_2\text{-MnO}_2$  electrodes at a scan rate of 30  $\text{mV s}^{-1}$  (a) and deconvolutions of the total capacitance into surface element (solid part) and insertion element (shaded part) for the (b)  $\text{TiO}_2\text{-MnO}_2$  and (c)  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  electrodes measured at 30 and 100  $\text{mV s}^{-1}$ . The bar graphs represent the contribution of each element at various scan rates.

The calculated  $C_{\text{sp}}$  value of the  $\text{MnO}_2$  electrode increased from 114.0  $\text{F g}^{-1}$  to 141.5  $\text{F g}^{-1}$  after the  $\text{TiO}_2$  incorporation. The CVs of the half-cell electrodes before and after  $\text{TiO}_2$  incorporation measured at various scan rates are shown in Fig. S3.† More quantitative analyses on the effect of the  $\text{TiO}_2$  incorporation were carried out by deconvoluting the capacitive elements of the electrodes. At a given applied voltage, a current is regarded as a sum of the two capacitive elements, namely a surface element ( $k_1v$ ) and faradaic insertion element ( $k_2v^{1/2}$ ), according to the following equation;<sup>35,36</sup>

$$i(V) = k_1v + k_2v^{1/2} \quad (2)$$

where  $v$  is the scan rate and  $k_1$ ,  $k_2$  are constants. The process of extracting elements was described elsewhere.<sup>37</sup>

The deconvoluted CV graphs for the  $\text{MnO}_2$  electrodes at scan rates of 30  $\text{mV s}^{-1}$  and 100  $\text{mV s}^{-1}$  are shown in Fig. 2b. The  $k_1v$  plot corresponding to the surface capacitive element is shown as a solid area, and the other shaded area corresponds to the insertion element. The surface element of the  $\text{TiO}_2$ -free  $\text{MnO}_2$  electrode was approximately 34.9  $\text{F g}^{-1}$ , which was virtually independent of the scan rate.<sup>36</sup> However, the insertion element decreased from 79.0  $\text{F g}^{-1}$  at 30  $\text{mV s}^{-1}$  to 23.8  $\text{F g}^{-1}$  at 100  $\text{mV s}^{-1}$  because the diffusion-controlled insertion was less accessible at a higher scan rate.<sup>38,39</sup> The contribution of the insertion element in the total capacitance hence decreased from 69.3% at 30  $\text{mV s}^{-1}$  to 40.5% at 100  $\text{mV s}^{-1}$ . The incorporation of the  $\text{TiO}_2$  NPs significantly increased the surface element to 69.2  $\text{F g}^{-1}$ . The insertion element also increased to 72.3  $\text{F g}^{-1}$  at 30  $\text{mV s}^{-1}$  and 33.0  $\text{F g}^{-1}$  at 100  $\text{mV s}^{-1}$ . As a result, at 30  $\text{mV s}^{-1}$ , the total specific capacitance of the  $\text{TiO}_2$ -incorporated  $\text{MnO}_2$  electrode (141.5  $\text{F g}^{-1}$ ) was 1.24 times larger than that of the  $\text{TiO}_2$ -free  $\text{MnO}_2$  electrode (114.0  $\text{F g}^{-1}$ ). At a high scan rate, the effect of the  $\text{TiO}_2$  incorporation was more apparent, reaching a 1.73 times increase in  $C_{\text{sp}}$  from 58.8  $\text{F g}^{-1}$  to 102.2  $\text{F g}^{-1}$  at 100  $\text{mV s}^{-1}$ . This enhancement in specific capacitance and voltammetric response is probably attributed to the reduced resistance of the electrode due to incorporation of electrically more conductive  $\text{TiO}_2$  NPs. The resistive elements of the electrodes was evaluated by electrochemical impedance spectroscopy (EIS) measurements (Fig. 3a and b). The diameter of the round curve in the high-frequency region of the Nyquist plots, indicative of the charge-transfer resistance,  $R_{\text{ct}}$ , were significantly smaller for the  $\text{TiO}_2$ -incorporated electrodes. The diffusive resistance,  $R_d$ , which is inversely proportional to the slope of the line in the low-frequency region, also decreased by the  $\text{TiO}_2$  incorporation.

While the incorporation of the  $\text{TiO}_2$  NPs improved both the capacitive elements of the  $\text{MnO}_2$ -based electrode, only the insertion element was increased in the case of the  $\text{Fe}_2\text{O}_3$  electrode (Fig. 2c). The scan-rate-independent surface element of the  $\text{TiO}_2$ -free  $\text{Fe}_2\text{O}_3$  electrode was approximately 25.2  $\text{F g}^{-1}$ , while the insertion element was 35.6  $\text{F g}^{-1}$  (58.1%) at 30  $\text{mV s}^{-1}$  and 16.6  $\text{F g}^{-1}$  (42.4%) at 100  $\text{mV s}^{-1}$ . For the  $\text{TiO}_2\text{-Fe}_2\text{O}_3$  electrode, the insertion elements were significantly larger over the whole range of the scan rate, e.g. 47.2  $\text{F g}^{-1}$  (78.0%) at 30  $\text{mV s}^{-1}$  and 19.3  $\text{F g}^{-1}$  (59.3%) at 100  $\text{mV s}^{-1}$ , indicating that the incorporation of the  $\text{TiO}_2$  NPs improved the diffusion of the





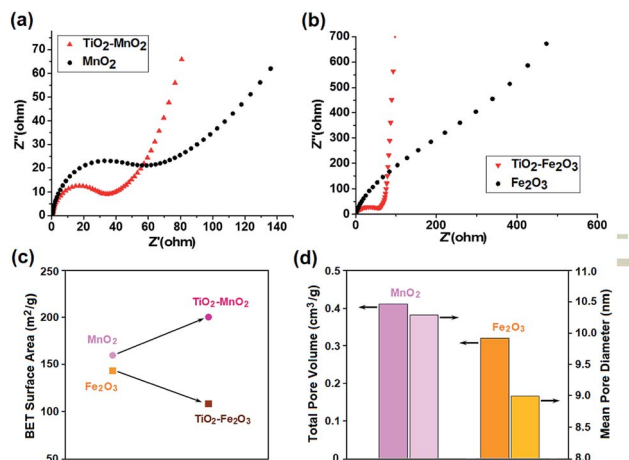


Fig. 3 Nyquist plots of (a) MnO<sub>2</sub>- and (b) Fe<sub>2</sub>O<sub>3</sub>-based electrodes, and (c) BET specific surface area and (d) total pore volume and mean pore diameter of the synthesized TMO NPs.

charge carriers in the Fe<sub>2</sub>O<sub>3</sub> electrode. In contrast, the TiO<sub>2</sub> incorporation decreased the surface elements from 25.2 F g<sup>-1</sup> to 13.3 F g<sup>-1</sup>. The opposite effect of the TiO<sub>2</sub> incorporation on the surface elements of the MnO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub> electrode is probably related to the change of their surface area. The BET isotherms, with an adsorption-desorption hysteresis loop as shown in Fig. S4,† indicate that the synthesized MnO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub> NPs can be categorized as a mesoporous adsorbents.<sup>40</sup> This porous nature of the electrode materials is favourable for the application to supercapacitor electrodes due to the increased surface sites for the energy storage.<sup>41–44</sup> While the specific surface area of the MnO<sub>2</sub> NPs increased from 137.5 m<sup>2</sup> g<sup>-1</sup> to 164.3 m<sup>2</sup> g<sup>-1</sup> by the TiO<sub>2</sub> incorporation, that of the Fe<sub>2</sub>O<sub>3</sub> NPs decreased from 142.5 m<sup>2</sup> g<sup>-1</sup> to 107.5 m<sup>2</sup> g<sup>-1</sup> (Fig. 3c). Although it is not clear yet, the incorporation of TiO<sub>2</sub> NPs on the MnO<sub>2</sub> NPs with larger pore volume and mean pore diameter (Fig. 3d) might lead to more morphological hierarchization. On the other hand, the TiO<sub>2</sub> incorporation on Fe<sub>2</sub>O<sub>3</sub> NPs seemed to result in a reduction of contact sites with the electrolyte. All the deconvolution results are summarized in Tables S1 and S2.†

Based on the results of the two composite TMO NPs-based single electrode cells, an asymmetric full-cell consisting of TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>-MnO<sub>2</sub> electrodes was fabricated. Since the electrochemical redox reactions of the two electrodes occur in entirely different voltage ranges, *i.e.* -1.0–0.0 V for the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and 0.0–1.0 V for the TiO<sub>2</sub>-MnO<sub>2</sub> electrode, the asymmetric combination of the two electrodes was expected to significantly increase the specific energy of the device. The schematic of the ASC device is shown in the inset of Fig. 4c. For comparison, symmetric supercapacitors, *i.e.* devices based on TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>-MnO<sub>2</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> electrodes, were also fabricated. Fig. 4a and b show the CV contours of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>-MnO<sub>2</sub> symmetric cell, respectively, at various scan rates from 10 mV s<sup>-1</sup> to 100 mV s<sup>-1</sup>. The calculated *C*<sub>sp</sub> values are plotted as a function of the scan rate (Fig. 4d). The *C*<sub>sp</sub> value of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> symmetric device was 35.5 F g<sup>-1</sup> measured at a scan rate of 30 mV s<sup>-1</sup>. This *C*<sub>sp</sub> value is approximately half the value of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> single electrode,

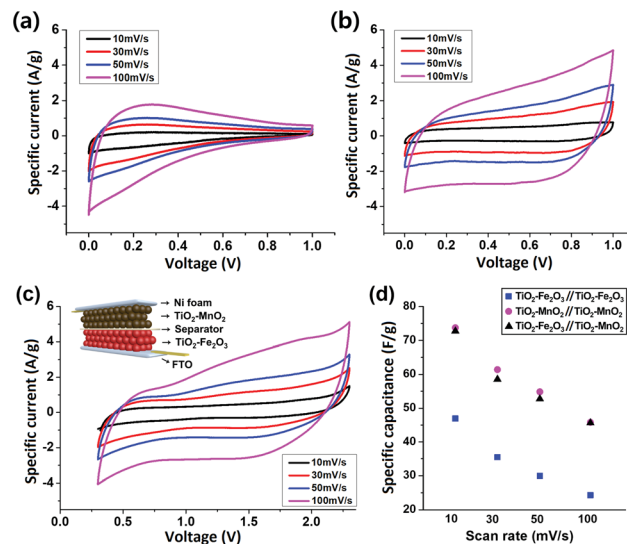


Fig. 4 Cyclic voltammograms of (a) TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> symmetric, (b) TiO<sub>2</sub>-MnO<sub>2</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> symmetric and (c) TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> asymmetric devices at various scan rates. The inset in (c) represents the schematic of the asymmetric device structure. The *C*<sub>sp</sub> values of the devices are plotted as a function of the scan rate in (d).

60.5 F g<sup>-1</sup>, according to the following equation for the *C*<sub>sp</sub> calculation of symmetric or asymmetric devices,

$$\frac{1}{C} = \frac{1}{m_+ C_+} + \frac{1}{m_- C_-} \quad (3)$$

where *m* is the mass, *C* is the specific capacitance, and + or - denotes the values for positive and negative electrodes, respectively. The *C*<sub>sp</sub> value gradually decreased as the scan rate increased, and reached 24.3 F g<sup>-1</sup> at 100 mV s<sup>-1</sup>. For the TiO<sub>2</sub>-MnO<sub>2</sub> symmetric device, the *C*<sub>sp</sub> decreased from 73.7 F g<sup>-1</sup> at 10 mV s<sup>-1</sup> to 45.8 F g<sup>-1</sup> at 100 mV s<sup>-1</sup>. The *C*<sub>sp</sub> values of the symmetric cells at various scan rates are plotted in Fig. 4d and summarized in Table S3.†

Prior to the assembly of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASCs, the mass ratio of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>-MnO<sub>2</sub> NPs was determined by the *C*<sub>sp</sub> values of the Fe<sub>2</sub>O<sub>3</sub>- and MnO<sub>2</sub>-based symmetric cells using the following equation in order to make each electrode contribute equivalent capacitance,

$$R = \frac{m_+}{m_-} = \frac{C_- \Delta V_-}{C_+ \Delta V_+} \quad (4)$$

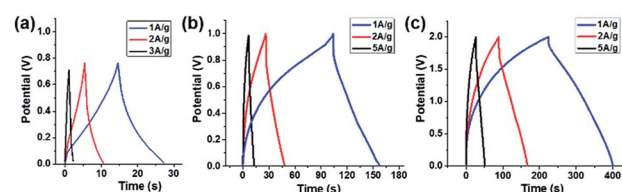


Fig. 5 (a) Galvanostatic charge-discharge curves of (a) TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> symmetric, (b) TiO<sub>2</sub>-MnO<sub>2</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> symmetric and (c) TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> asymmetric devices at various specific currents.



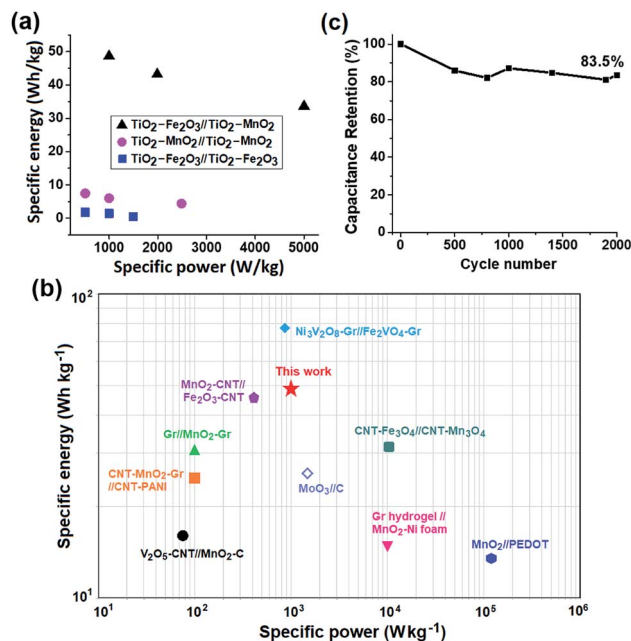


Fig. 6 Ragone plots for (a) Fe<sub>2</sub>O<sub>3</sub>- and MnO<sub>2</sub>-based devices and (b) other ASCs reported in the literature for comparison, and (c) capacitance retention of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC as a function of the number of GCD cycles at a specific current of 2 A g<sup>-1</sup>.

where  $\Delta V_+$  and  $\Delta V_-$  are the voltage windows of the positive and negative electrode, respectively. The measured mass of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>-MnO<sub>2</sub> NPs used in this work were 3.5 and 0.8 mg cm<sup>-2</sup>, respectively. The CVs of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC measured at various scan rates are shown in Fig. 4c, and the calculated  $C_{sp}$  values are plotted in Fig. 4d. A working voltage window of 2.0 V was determined by the results of the individual electrode. The  $C_{sp}$  values of the ASC were slightly smaller than the values of the TiO<sub>2</sub>-MnO<sub>2</sub>-based symmetric cell over the entire range of the scan rates. The largest  $C_{sp}$  value of 72.7 F g<sup>-1</sup> was obtained at a scan rate of 10 mV s<sup>-1</sup>, and the value decreased to 45.6 F g<sup>-1</sup> at 100 mV s<sup>-1</sup>. This scan rate retention of 62.7% was larger than 51.8% for the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> symmetric cell and 62.1% for the TiO<sub>2</sub>-MnO<sub>2</sub> symmetric cell, as shown in Fig. 4d, indicating a higher voltammetric response of the ASC.

The capacitive performance of the Fe<sub>2</sub>O<sub>3</sub>- and MnO<sub>2</sub>-based symmetric and asymmetric cells were also estimated by galvanostatic charge-discharge (GCD) measurements shown in Fig. 5. The  $C_{sp}$  value of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> symmetric cell was 12.8, 10.3, and 3.5 F g<sup>-1</sup> measured at a current density of 1, 2 and

3 A g<sup>-1</sup>, respectively (Fig. 5a). The considerably extended discharge time of the TiO<sub>2</sub>-MnO<sub>2</sub> symmetric and asymmetric cells (Fig. 5b and c) indicate the better capacitance of the MnO<sub>2</sub>-based electrode. The calculated  $C_{sp}$  values of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC were 87.5, 77.7, and 33.6 F g<sup>-1</sup> at a current density of 1, 2 and 5 A g<sup>-1</sup>, respectively. The obtained  $C_{sp}$  values at various current densities are summarized in Table S4.† In addition to the larger  $C_{sp}$  value of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC, the doubly extended voltage window contributed to the enhancement in the energy density of the device shown in the Ragone plots (Fig. 6a). The specific energy ( $E_{sp}$ ) and specific power ( $P_{sp}$ ) of the cells were calculated using the following equations,<sup>45,46</sup>

$$E_{sp} = \frac{5C_{sp}(\Delta V)^2}{36} \quad (5)$$

$$P_{sp} = \frac{3600E_{sp}}{\Delta t} \quad (6)$$

where  $\Delta V$  (V) is the applied voltage window and  $\Delta t$  (s) is the discharge time. As shown in the figure, the specific energies of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC are larger than those of the symmetric cells at the given specific power. The specific energy of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC reached 48.6 W h kg<sup>-1</sup> at a specific power of 1000 W kg<sup>-1</sup>. The  $E_{sp}$  values of the all-metal-oxide-NPs-based symmetric and asymmetric supercapacitors are summarized in Table 1. The obtained specific energy of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC is comparable to the metal oxide electrode-based ASCs reported in the literature, including CNT-Fe<sub>3</sub>O<sub>4</sub>||CNT-Mn<sub>3</sub>O<sub>4</sub>,<sup>47</sup> graphene (Gr) hydrogel||MnO<sub>2</sub>-Ni foam,<sup>48</sup> Gr||MnO<sub>2</sub>-Gr,<sup>49</sup> MnO<sub>2</sub>-CNT||Fe<sub>2</sub>O<sub>3</sub>-CNT,<sup>49</sup> CNT-MnO<sub>2</sub>-Gr||CNT-PANI,<sup>50</sup> V<sub>2</sub>O<sub>5</sub>-CNT||MnO<sub>2</sub>-C,<sup>51</sup> Ni<sub>3</sub>V<sub>2</sub>O<sub>8</sub>-Gr||Fe<sub>2</sub>VO<sub>4</sub>-Gr,<sup>52</sup> MnO<sub>2</sub>-||PEDOT<sup>53</sup> and MoO<sub>3</sub>||C<sup>54</sup> ASCs, as shown in Fig. 6b. The cycle stability of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC was also evaluated by repetitive GCD measurement cycles at a specific current of 2 A g<sup>-1</sup> (Fig. 6c). The  $C_{sp}$  retention after 2000 GCD cycles was 83.5% of the initial value. The apparent change in the surface morphology of the electrodes was not observed after 2000 GCD cycles (Fig. S5†), also indicating the good structural stability of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC electrodes.

## Conclusions

An all-metal-oxide-NPs-based ASC with electrodes made of TiO<sub>2</sub> NPs-incorporated Fe<sub>2</sub>O<sub>3</sub> and MnO<sub>2</sub> NPS was successfully fabricated. In the MnO<sub>2</sub> NPs-based single electrode, the incorporation of the TiO<sub>2</sub> NPs improved the specific capacitance from

Table 1 Summary of the capacitive properties of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>-MnO<sub>2</sub> NPs-based symmetric and asymmetric devices

Capacitive properties	TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub>   TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> symmetric	TiO <sub>2</sub> -MnO <sub>2</sub>   TiO <sub>2</sub> -MnO <sub>2</sub> symmetric	TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub>   TiO <sub>2</sub> -MnO <sub>2</sub> asymmetric
$C_{sp}$ measured at 10 mV s <sup>-1</sup> (F g <sup>-1</sup> )	46.9	73.7	72.7
Voltammetric retention	51.8%	62.1%	62.7%
$E_{sp}$ at $P_{sp}$ of 1000 W kg <sup>-1</sup> (W h kg <sup>-1</sup> )	1.4	6.0	48.6



114.0 F g<sup>-1</sup> to 141.5 F g<sup>-1</sup> at a scan rate of 30 mV s<sup>-1</sup>. The deconvolution of the capacitive elements indicated that this enhancement was attributed to an increase in both the surface element and insertion element. However, for the Fe<sub>2</sub>O<sub>3</sub> NPs-based electrode, the insertion element was increased while the surface capacitive element was reduced so that the total capacitance did not improve apparently. An ASC comprised of these two composite TMO electrodes, the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>-MnO<sub>2</sub> electrodes, was fabricated. The C<sub>sp</sub> value of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC reached 72.7 F g<sup>-1</sup> measured at a scan rate of 10 mV s<sup>-1</sup>, which is slightly lower than the value for the TiO<sub>2</sub>-MnO<sub>2</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> (73.7 F g<sup>-1</sup>) symmetric capacitors. However, the ASC could operate over a voltage window of 2.0 V, twice as large as that of the symmetric devices, which resulted in a significant enhancement in the specific energy of the device. The specific energy of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC was 48.6 W h kg<sup>-1</sup> at a specific power of 1000 W kg<sup>-1</sup> while that of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>-MnO<sub>2</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> symmetric capacitor was 1.4 and 6.0 W h kg<sup>-1</sup>, respectively. The C<sub>sp</sub> retention of the TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>||TiO<sub>2</sub>-MnO<sub>2</sub> ASC was approximately 83.5% of the initial value after 2000 GCD cycles. All the benefits, *i.e.* wide operating voltage window and comparable specific capacitance, demonstrate that an all-metal-oxide-NPs-based ASC is a promising architecture for high energy density supercapacitors. It also implies that the device performance will be further improved by optimizing the type and composition of the TMO NPs used.

## Conflicts of interest

There is no conflicts to declare.

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