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# Preparation of mesoporous SnO<sub>2</sub>-SiO<sub>2</sub> composite as electrodes for lithium batteries

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Mesoporous SnO<sub>2</sub>-SiO<sub>2</sub> composite stable up to 600 °C with a BET surface area of 350 m<sup>2</sup> g<sup>-1</sup> and an average pore size of 3.4 nm is successfully prepared, which exhibits promising cycling properties as anodes for lithium batteries.

Following the discovery of the M41S family of mesoporous silicates using supramolecular templating approach,<sup>1,2</sup> mesoporous materials have attracted considerable attention because of their tunable pore size, narrow pore size distribution, and remarkably large surface areas, which make them ideal candidates for catalysts, molecular sieves, and electrodes for solid-state ionic devices. The ordering in these materials is a consequence of a self-assembly process in an aqueous solution containing organic surfactants (anionic, cathodic, or neutral) and inorganic cations or anions. To date, a wide range of mesoporous materials have been prepared using the structure-directing functions of electrostatic, hydrogen-bonding, covalent bonding and van der Waals interactions associated with amphiphilic surfactant molecules.<sup>3-10</sup>

Tin-based composite oxides are promising candidates for anodes in lithium batteries because of their much larger reversible capacity compared to carbonaceous materials. In this study, mesoporous SiO<sub>2</sub> stable up to 600 °C has been prepared using Brij 56 as a structure-directing agent and TEOS as precursor in an aqueous solution.† Further, a tin compound is introduced into porous SiO<sub>2</sub> using a sol-gel technique to form SnO<sub>2</sub>-SiO<sub>2</sub> composite. The objective of our study is to create a nano-structured SnO<sub>2</sub>-SiO<sub>2</sub> electrodes for lithium batteries. The structural stability of the tin-based materials during cycling is a major barrier to the successful application of this material as anodes in Li-batteries.<sup>11</sup> Our approach to improving the structural stability is to incorporate a tin compound into a mesoporous SiO<sub>2</sub> matrix, which is structurally stable and hence offers structural stability to the nanocomposite electrode. The mesoporous SnO<sub>2</sub>-SiO<sub>2</sub> structure will facilitate the penetration of the liquid electrolyte into the electrodes and hence increase the rate of charge and discharge.

Shown in Fig. 1 are XRD patterns of mesoporous SiO<sub>2</sub> powder samples before and after calcination at 600 °C for 2 h prepared using Brij 56 as surfactant. The XRD pattern of the as-synthesized powders indicates that the surfactant molecules were organized into a hexagonal structure when aged at room temperature for 2 d. The peak at about 1.2° corresponds to the (100) reflection, which has a *d*-spacing of 6.8 nm. Thermogravimetric analysis shows that Brij 56 surfactant is completely removed upon calcination in air at 400 °C for 1 h. The appearance of a low-angle diffraction peak of the SiO<sub>2</sub> powder calcined at 600 °C for 2 h indicates that mesoscopic order is preserved upon removal of the surfactant by calcination, although the structure contracted slightly as evidenced from a slight shift of the XRD peak to a higher angle. The corresponding *d*-spacing is reduced to about 6.3 nm. The increased intensity of the XRD peak of the calcined SiO<sub>2</sub> indicates that the ordering of the mesostructure is improved during calcination. Shown in Fig. 1(c) is the XRD pattern of a SnO<sub>2</sub>-SiO<sub>2</sub> composite. The peak is broader than that of pure SiO<sub>2</sub>, suggesting that either the degree of ordering was reduced or the

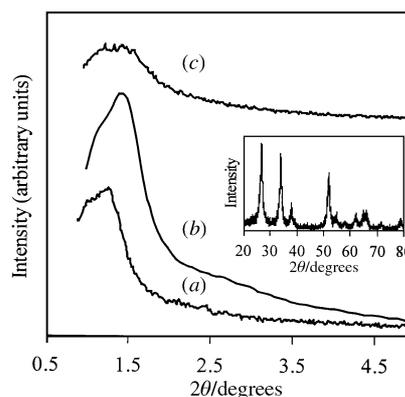


Fig. 1 Representative small-angle X-ray powder diffraction patterns of (a) as-synthesized SiO<sub>2</sub>, (b) SiO<sub>2</sub> calcined at 600 °C for 2 h, and (c) SnO<sub>2</sub>-SiO<sub>2</sub> composite calcined at 600 °C for 2 h. The wide-angle X-ray diffraction pattern of SnO<sub>2</sub>-SiO<sub>2</sub> composite is shown in the inset.

size distribution of the mesopores was broadened. However, the position of the peak did not change, implying that the *d*-spacing remained the same upon incorporating tin species into the pores of the mesoporous SiO<sub>2</sub>. Further, the wide-angle XRD pattern shown in the inset in Fig. 1 indicates that the SnO<sub>2</sub> incorporated into the mesoporous SiO<sub>2</sub> is crystalline, rather than amorphous.

Shown in Fig. 2 are representative TEM images of SiO<sub>2</sub> and SnO<sub>2</sub>-SiO<sub>2</sub> samples after calcination at 600 °C for 2 h. Mesostructures with short-range hexagonal order can be seen and the corresponding *d*-spacings are 6.3 nm for both SiO<sub>2</sub> and SnO<sub>2</sub>-SiO<sub>2</sub> composite, which are close to those determined from the XRD patterns. The nitrogen adsorption isotherms of the SiO<sub>2</sub> and SnO<sub>2</sub>-SiO<sub>2</sub> samples after calcination at 600 °C for 2 h are shown in Fig. 3 and the calculated Brunauer-Emmett-Teller (BET) surface areas are 1100 m<sup>2</sup> g<sup>-1</sup> for SiO<sub>2</sub> and 350 m<sup>2</sup> g<sup>-1</sup> for SnO<sub>2</sub>-SiO<sub>2</sub> composite, respectively. The gas-accessible surface area of the mesoporous SnO<sub>2</sub>-SiO<sub>2</sub> composite was greatly reduced due to partial occupation of the pores by

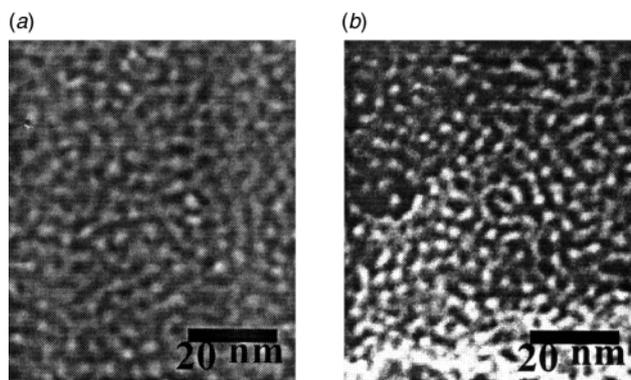
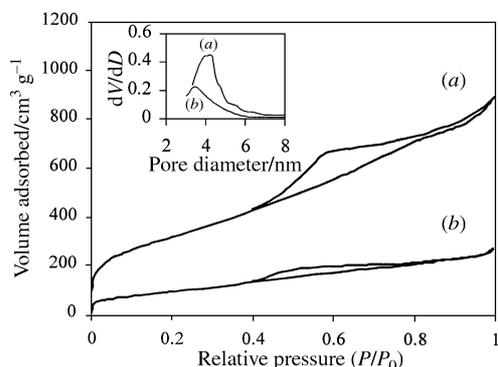


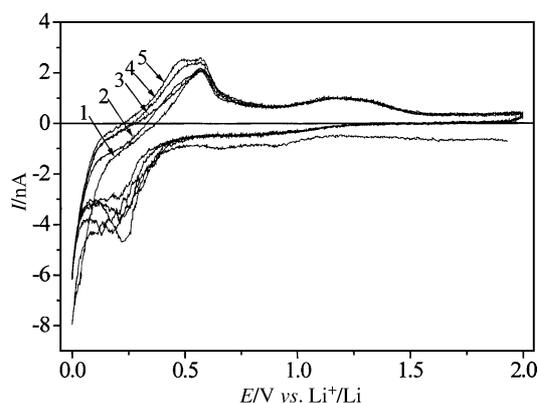
Fig. 2 TEM micrographs of (a) 600 °C calcined mesoporous SiO<sub>2</sub> and (b) mesoporous SnO<sub>2</sub>-SiO<sub>2</sub> composite.



**Fig. 3** Representative nitrogen adsorption and desorption isotherms for (a)  $\text{SiO}_2$  and (b)  $\text{SnO}_2\text{-SiO}_2$  composite after calcination at  $600^\circ\text{C}$  for 2 h. Corresponding BJH pore size distributions are shown in the inset.

the tin species incorporated into the mesoporous  $\text{SiO}_2$ . Both nitrogen isotherm curves have a well-defined step for the relative pressure  $P/P_0$  ranging from 0.4 to 0.8, a characteristic of the filling of the framework-confined mesopores,<sup>12</sup> suggesting that both  $\text{SiO}_2$  and  $\text{SnO}_2\text{-SiO}_2$  samples are mesoporous after calcination at  $600^\circ\text{C}$  for 2 h. As shown in the inset in Fig. 3, the average pore size in the  $\text{SiO}_2$  structure is 4.0 nm while that in the  $\text{SnO}_2\text{-SiO}_2$  composite is 3.4 nm, implying that a thin  $\text{SnO}_2$  layer has been incorporated into the channel surface of the mesoporous  $\text{SiO}_2$ .

The electrochemical behavior of the obtained  $\text{SnO}_2\text{-SiO}_2$  composite oxide is further studied using cyclic voltammetry. Shown in Fig. 4 are the cyclic voltammograms (CVs) of a mesoporous  $\text{SnO}_2\text{-SiO}_2$  composite, as studied using a powder microelectrode in the potential range between 2.0 and 0 V (vs.  $\text{Li}^+/\text{Li}$ ) with a scan rate of  $0.2\text{ mV s}^{-1}$ . The potential was swept from 2.0 V in the cathodic direction down to the set limit (0 V) and then in the anodic direction. Two very small irreversible reduction peaks appeared near 0.6 and 0.9 V, respectively, in the CV of the first cycle. This is quite different from the CVs observed for tin-based composite electrodes in the literature,<sup>13,14</sup> in which there is only one large irreversible reduction peak around 0.9 V in the first sweep. It is well known that this large irreversible reduction peak is due to the *in situ* electrochemical reduction of SnO or  $\text{SnO}_2$  by lithium to metallic tin and  $\text{Li}_2\text{O}$ ,<sup>15</sup> representing a large irreversible capacity loss for tin-based composite materials in the first cycle, which is still a major barrier to the successful application of these materials as anodes in Li-batteries.<sup>14</sup> In this work, even though it is still not



**Fig. 4** Cyclic voltammograms (CVs) of a mesoporous  $\text{SnO}_2\text{-SiO}_2$  composite as studied electrode using a powder microelectrode technique. The number adjacent to each CV represents the order of the cycles.

clear what the two tiny irreversible reduction peaks (observed for the mesoporous  $\text{SnO}_2\text{-SiO}_2$  composite) correspond to, it is anticipated that the mesoporous  $\text{SnO}_2\text{-SiO}_2$  composite as an anode for a lithium battery would display much less irreversible capacity loss during the first cycle. Further, the reversible redox peaks in the range of 0.1–0.7 V in the first five cycles of the CVs show very little change, an indication of good cyclability of such a mesoporous  $\text{SnO}_2\text{-SiO}_2$  composite electrode. The electrochemical behavior of  $\text{SnO}_2$  in mesoporous  $\text{SnO}_2\text{-SiO}_2$  composites as well as the long-term charge–discharge cycling behavior of the composite electrodes in a lithium cell are still under investigation and will be reported in subsequent communications.

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## Notes and references

† In a typical preparation using Brij 56 as the structure-directing agent, 1.093 g Brij 56 was dissolved in 80 ml  $\text{H}_2\text{O}$  by stirring at room temperature. 2.667 g tetraethyl orthosilicate (TEOS) was added to the Brij 56 solution and the solution was stirred at room temperature for 2 h. Subsequently, 1.333 ml 0.2 M NaF was added to the above solution and the solution was stirred at room temperature for 2 h while a milky sol was obtained. The milky sol was placed at room temperature for 2 d and a white precipitate formed progressively. The precipitate was finally filtered off, washed 5 times using distilled  $\text{H}_2\text{O}$ , dried at  $60^\circ\text{C}$  in a vacuum oven and finally calcined in air at  $600^\circ\text{C}$  for 2 h to remove the surfactant. Incorporation of tin compound into the pores of  $\text{SiO}_2$  was achieved by immersing mesoporous  $\text{SiO}_2$  powder into tin nitrate solution and then drying at  $40^\circ\text{C}$  under vacuum. Mesoporous  $\text{SnO}_2\text{-SiO}_2$  composite was obtained by calcining the dried tin nitrate– $\text{SiO}_2$  powder at  $600^\circ\text{C}$  for 2 h in air. A powder microelectrode was used to study the electrochemical performance of mesoporous  $\text{SnO}_2\text{-SiO}_2$  composite in 1 M  $\text{Li}(\text{SO}_2\text{CF}_3)_2\text{EC}+\text{DMC}$  electrolyte solution.

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