

course of the first few cycles. Compared to the  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres, a much lower capacity of only 260 mA h/g is delivered at the end of the 38 cycles. This evidently proves that the remarkably positive effect of the interconnected carbon layer in the nanospheres. It is well-known that during the charge–discharge process, the  $\text{Fe}_3\text{O}_4$ -based anode surface would be covered by a solid-electrolyte interphase (SEI) film, which forms due to the reductive decomposition of the organic electrolyte [9–24]. For the  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres, a thin passivating SEI can form around the outer carbon layer during the first few cycles, and its further formation is terminated due to the electronically insulating nature of the SEI. Meanwhile, during the formation of a stable thin SEI around the outer carbon layer in the first few cycles, the capacity of the anode of  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres degrades rapidly [10,13,15,16]. After the formation of a stable SEI, their capacity maintains well and thus the anode of  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres presents excellent cycling performance. However, in the case of bare  $\text{Fe}_3\text{O}_4$  nanoparticles, the SEI will rupture due to the mechanical strain generated by the volume expansion/contraction during cycling and thus the electrode surface would be cyclically exposed to the electrolyte, which results in continual formation of very thick SEI films and accordingly continual consuming of electrolyte. The cyclically rupture and growth of SEI can cause low Coulombic efficiency, higher resistance to ionic transport, and low electronic conductivity of the whole electrode. Therefore, the capacity of the anode of bare  $\text{Fe}_3\text{O}_4$  nanoparticles de-

creases rapidly and their cycling performance is much worse than that of the  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres. In order to further investigate the effect of the outer carbon layer on the electrochemical performance of the  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres, we also tested the cycling performance of the bare carbon obtained by removing the  $\text{Fe}_3\text{O}_4$  from the  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres, the result is shown in Fig. 5c. As can be seen, the bare carbon shows a very low capacity of about 210 mA h/g, but its cycling performance is very excellent. This indicates that the outer carbon layer might contribute little to the Li-storage capacity of the  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres, but be very beneficial for improving the structural stability of the  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres.

Besides their outstanding reversible capacity and cycling stability, these  $\text{Fe}_3\text{O}_4/\text{C}$  electrodes also exhibit impressive rate performance. Fig. 5(d) shows the rate capability of  $\text{Fe}_3\text{O}_4/\text{C}$  electrode: after the rate was increased to 10 C (9240 mA/g) and capacities were recorded, the charge–discharge rates were reduced from 9240 (10 C) to 92.4 mA/g (0.1 C) again. It can be seen that the charge and discharge capacities decrease as the charge–discharge rates increase, which is caused by the low diffusion rate of the lithium ion into anodes at high rates [3–5]. However, the  $\text{Fe}_3\text{O}_4/\text{C}$  anode maintains much more stable charge and discharge capacities at higher rates (1, 2, 5 and 10 C) than that at lower rates (0.1 and 0.2 C). This phenomenon is also shown in other works [22–24]. According to the kinetics equation of electrode material, i.e.  $\tau = L^2/2D$ , where  $\tau$  is the diffusion time,  $L$  is the diffusion distance, and  $D$  is the  $\text{Li}^+$  chemical diffusion coeffi-

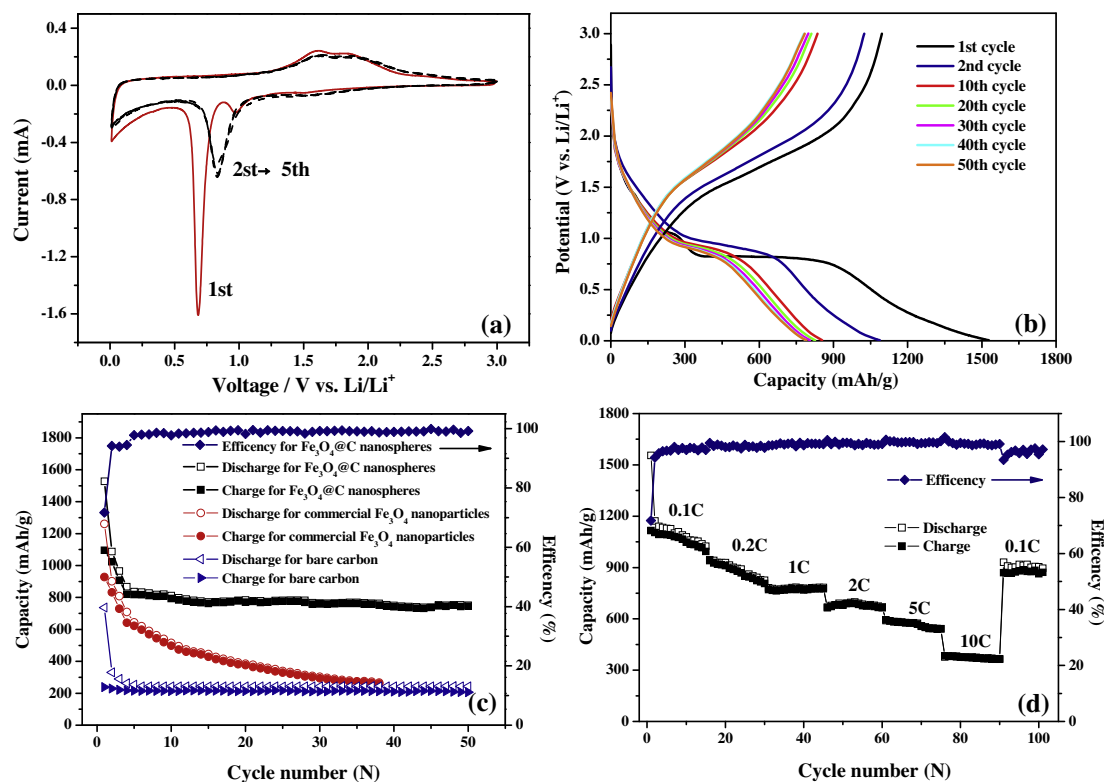


Fig. 5 – (a) CV of the interconnected  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres in a voltage range of 0.01–3.0 V at a scanning rate of 0.1 mV/s. (b) Discharge/charge voltage profiles cycled at the 1st, 2nd, 10th, 20th, 30th, 40th, and 50th cycle of the  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres between 0.005 and 3.00 V at a current density of 924 mA/g. (c) Comparative cycling performance of interconnected  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres, commercial  $\text{Fe}_3\text{O}_4$  nanoparticles and bare carbon without  $\text{Fe}_3\text{O}_4$  at a current density of 924 mA/g. (d) The rate capability of interconnected  $\text{Fe}_3\text{O}_4/\text{C}$  nanospheres at the rates between 0.1 and 10 C (1 C = 924 mA/g).