



# Effect of Lorentz force on the electrochemical performance of lithium-ion batteries



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## ABSTRACT

Lorentz force theory demonstrates that electric current density and magnetic force are proportional, indicating that they compensate each other. In a battery operated at high magnetic forces, the electrons in the active material move fast in a specific magnetic field.  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub>, a highly magnetic material, is used to prepare LiFePO<sub>4</sub> electrodes to study the effect of the Lorentz force on lithium-ion battery performance. The magnetic field created by  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> induces magnetic forces on the charged LiFePO<sub>4</sub> particles, accelerating electron movement. Superconducting quantum interference measurements reveal that saturation magnetization and remanence are prominent when  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> is added to the LiFePO<sub>4</sub> electrodes. The LiFePO<sub>4</sub> electrode containing 15 wt%  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> led to superior battery capacity (69.8 mAh g<sup>-1</sup> at 10C) compared with the pure LiFePO<sub>4</sub> electrode (1.8 mAh g<sup>-1</sup> at 10C). In this study, Lorentz force theory is applied to improve the specific capacity and cycle life at high current rates of a battery containing LiFePO<sub>4</sub> cathode materials, suggesting that incorporating  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> into the cathode is an easy and cheap strategy for increasing the power density and cycle life of lithium-ion batteries.

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## 1. Introduction

Battery testing equipment produces an electric field that is applied to the cell to cause a drift of electrons and ions between active materials and electrolytes during charge–discharge processes. The Lorentz force is the combination of the electric and magnetic forces on a moving point charge resulting from the electromagnetic fields [1,2].

Recently, several papers have discussed magnetic effects in lithium-ion batteries. Feng et al. synthesized a series of nanocrystalline cobalt ferrite powders to evaluate the effect of their microstructure and crystalline size on their magnetostriction [3]. Xi et al. discovered that large ionic radius substitution significantly affects the interactions between crystalline structures because of their saturation magnetization, magnetostriction coefficients, and strain derivatives [4]. Nature Energy published two papers concerning the magnetic control of sacrificial features, which was used to create directional pore arrays in lithium-ion electrodes [5] and to fabricate anodes with an out-of-plane aligned architecture using a weak external magnetic field [6]. However, none of the aforementioned studies resulted in clear findings concerning the relationship between electrochemical performance and magnetic properties regarding cathode material research.

In this study, the Lorentz force was discovered to affect the properties of lithium-ion batteries containing cathodes comprising a mixture of LiFePO<sub>4</sub> (LFP) and  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub>.  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> exhibits spontaneous ferromagnetic ordering [7] below its Curie temperature (645 °C) [8]. The magnetic field around  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> exerts a magnetic force on the charged LFP particles and thus accelerates electron and ion movements. The high Curie temperature and chemical stability of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> have led to its widespread use as a magnetic material in electronic recording media [9].  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> is used as an anode [10–12] and insulator [13], and as such, it cannot contribute to specific capacity when used in part of the cathode.

To determine the resistance and magnetic properties of the fabricated electrodes, sheet resistance and hysteresis loop measurements were performed for ingot and powder samples with various LFP: $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> weight ratios. To verify that the improvements to battery capacity were due to Lorentz force effects, several measurements, such as rate capability and cyclability, were conducted.

## 2. Experimental details

Commercial LFP powder (Aleees, Taiwan) was selected as the active cathode material, and  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> powder (98%) was purchased from Alfa Aesar (Haverhill, USA). Scanning electron microscopy was used to measure the particle sizes of LFP and  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub>, which were 500–550 and 20–30 nm, respectively. For the sheet resistance measurements, ingots

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**Table 1**

The remanence at 0 Oe and the saturation magnetization at 10,000 Oe of the electrodes with various  $\text{LiFePO}_4:\gamma\text{-Fe}_2\text{O}_3$  weight ratios.

Sample	Remanence/EMU $\text{g}^{-1}$	Saturation magnetization at 10000 Oe/EMU $\text{g}^{-1}$
0FO	$-4.18 \times 10^{-4}$	0.50
5FO	0.91	4.32
10FO	1.66	7.63
15FO	2.72	11.75
20FO	3.66	15.33

**Table 2**

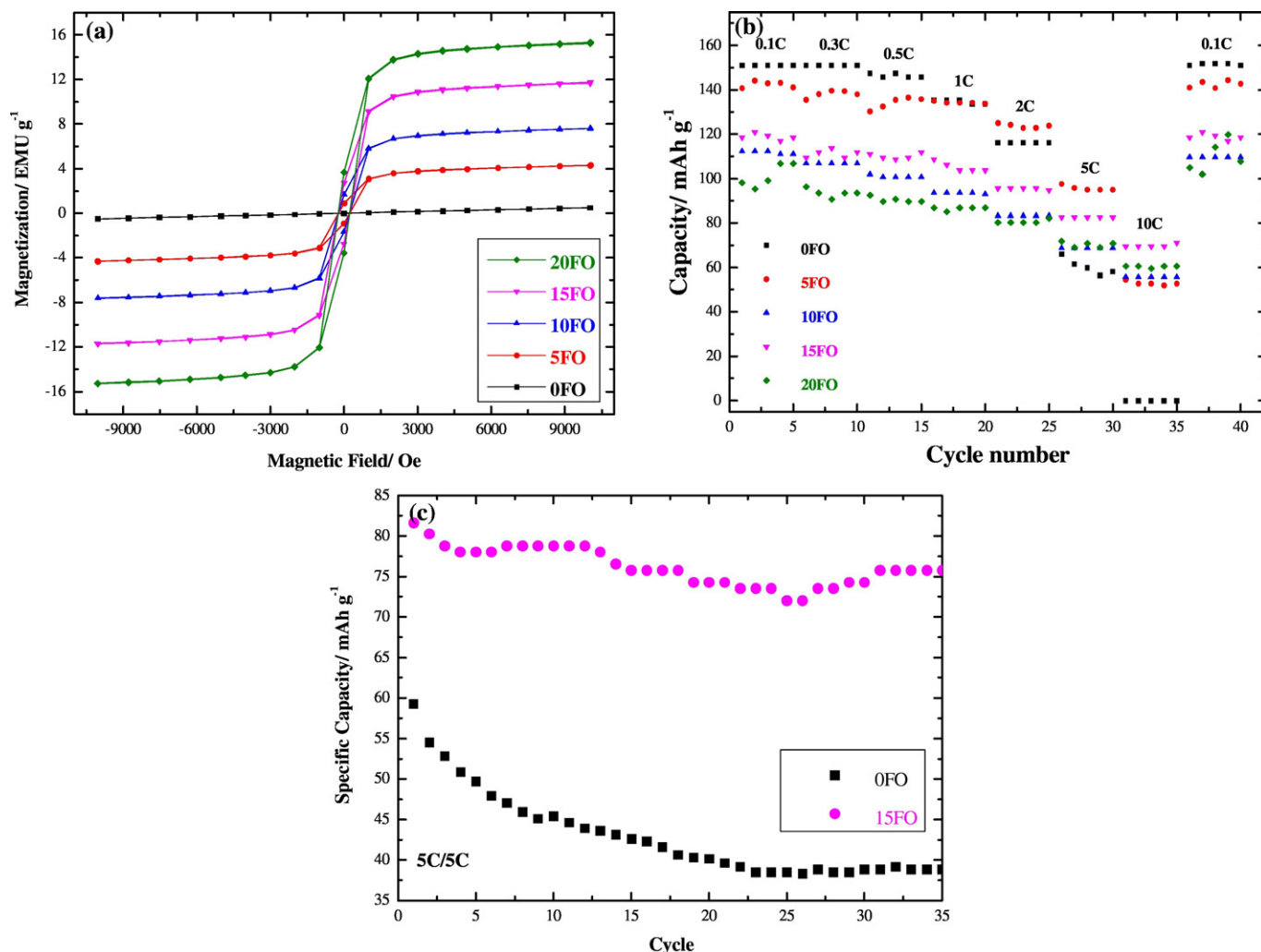
The sheet resistance of the pellet samples comprising various  $\text{LiFePO}_4:\gamma\text{-Fe}_2\text{O}_3$  ratios.

Sample	Sheet resistance/ $\Omega \text{ cm}^{-1}$
0FO	$1.43 \times 10^3$
5FO	$5.18 \times 10^4$
10FO	$1.33 \times 10^5$
15FO	$1.56 \times 10^5$
20FO	$2.78 \times 10^5$
Maghemite	$7.81 \times 10^5$

were prepared from the commercial LFP and  $\gamma\text{-Fe}_2\text{O}_3$  powders using a hydraulic machine at a pressure of  $300 \text{ kg cm}^{-2}$ . Ingots with LFP: $\gamma\text{-Fe}_2\text{O}_3$  ratios of 80:0, 75:5, 70:10, 65:15, and 60:20—named 0FO, 5FO,

10FO, 15FO, and 20FO, respectively—were prepared in the same manner. The ingots had a thickness of approximately 0.3 cm. The sheet resistances of the ingot samples were measured through the placement of a four-point probe resistivity tester on their surface. The hysteresis loop measurements were performed using a superconducting quantum interference device (SQUID). The hysteresis loops were measured at 298 K, and the magnetic field applied was between +10,000 and -10,000 Oersted (Oe). The magnetization of the samples was measured at every 1000 Oe interval. The remanence at 0 Oe and the saturation magnetization at 10,000 Oe were also recorded for each sample and are presented in Table 1.

For the rate capability and cyclability tests, the LFP and  $\gamma\text{-Fe}_2\text{O}_3$  powders were mixed in various weight ratios. The LFP cathodes comprised LFP (80 - x wt%),  $\gamma\text{-Fe}_2\text{O}_3$  (x wt%), poly(vinylidene fluoride) (8 wt%) as a binder, and conductive carbon KS-6 (7 wt%) and Super P (5 wt%) as conductive additives. The loadings of the LFP active material in 0FO, 5FO, 10FO, 15FO, and 20FO electrodes are 1.248, 1.170, 1.092, 1.014, and 0.936 mg, respectively. All the electrodes are approximately 7.3 mg, including aluminum foil, LFP active material, conductive carbons, and  $\gamma\text{-Fe}_2\text{O}_3$ . The electrolyte consisted of  $\text{LiPF}_6$  (1.0 M) dissolved in an ethylene carbonate-propylene carbonate-diethyl carbonate (3:2:5 in volume) mixed solvent. The electrode materials were tested by assembling CR2032 coin-type cells with potentials ranging from 2.5 to 4.3 V on the battery testing equipment. The rate capability test had eight segments: 0.1C, 0.3C, 0.5C, 1.0C, 2.0C, 5.0C, 10C, and 0.1C. Each rate segment consisted of five charge-discharge cycles. The cyclability



**Fig. 1.** (a) The hysteresis loops, (b) the specific rate capacity, and (c) cycle performance of the mixed powder samples with various  $\text{LiFePO}_4:\gamma\text{-Fe}_2\text{O}_3$  weight ratios.

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