Bifunctional Sn-Carbon Additives for Enhanced Performance in Lithium-Ion Batteries

Hyeonsu Yang[1,2], Oi Lun Li*[1]

1. *Department of Materials Science and Engineering, Pusan National University*

2 Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 46241, Republic of Korea

2. *Interdisciplinary Graduate School of Engineering Sciences, Kyushu University*

6-1 Kasugakouen, Kasuga, Fukuoka 816-8580, Japan

**E-mail: helenali@pusan.ac.kr*

ABSTRACT

Traditional conductive additives, such as carbon black (CB), are essential in lithium-ion battery (LIB) electrodes to ensure efficient conductivity, yet their role is limited as they do not contribute to lithium storage capacity. This study presents a bifunctional Sn-doped carbon composite (Sn@C) designed to expand beyond a conductive role by actively enhancing lithium storage and overall electrochemical performance. The Sn@C composite, synthesized using plasma engineering, incorporates Sn nanoparticles uniformly distributed within a carbon matrix, achieving notable improvements in both conductivity and capacity. Specifically, Sn@C-500, annealed at 500 °C, exhibited ~10% higher reversible capacity and reduced internal resistance compared to conventional Super P carbon black. Electrochemical impedance spectroscopy (EIS) measurements further validated Sn@C-500's role in facilitating efficient charge transfer, confirming its dual functionality as an active and conductive additive. These results highlight the potential of Sn@C composites to increase LIB anode capacity and cycling stability, marking a significant step towards high-performance LIB applications through the integration of active materials within conductive matrices.

KEY WORDS

Conductive Additive, Sn-Carbon Composite, Lithium-Ion Battery Anode

1. INTRODUCTION

With the growing need for high-capacity and high-performance lithium-ion batteries, traditional conductive additives such as carbon black (CB) are increasingly inadequate due to their lack of lithium storage capability. Conductive additives in LIB electrodes have conventionally served to maintain electronic conductivity, yet this approach limits energy density, especially as demands rise for more powerful and efficient batteries.[1] To address these limitations, this study explores a bifunctional strategy, using Sn@C—a tin (Sn) nanoparticle-doped carbon matrix—as an "active" conductive additive that enhances lithium storage capacity while maintaining conductivity.[2] Tin, with a high theoretical capacity of 994 mAh g^{-1}, offers promising lithium alloying properties and intrinsic conductivity, making it an attractive candidate for advancing LIB anode materials.[3] The goal of this research is to develop a conductive additive that also serves as an active component, potentially increasing LIB energy density and rate capability.[4]

2. RESULTS

The structural and electrochemical properties of Sn@C composites varied with annealing temperature, resulting in three samples: Sn@C-Raw, Sn@C-500, and Sn@C-1000. TEM and HR-TEM imaging revealed that Sn@C-500 had the optimal structural characteristics, with well-dispersed Sn nanoparticles (approximately 20 nm) uniformly embedded in a carbon matrix (Fig. 1). This matrix retained a carbon black-like morphology with a network of mesopores and macropores, facilitating efficient lithium-ion transport while suppressing the expansion of Sn during cycling. EDS mapping confirmed a consistent dispersion of Sn throughout the material, contributing to stable conductivity across the electrode.

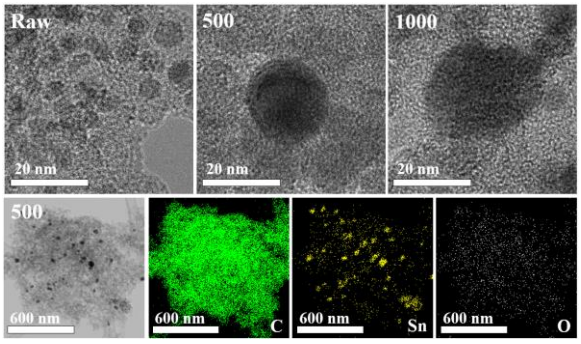

Fig. 1. TEM images and EDS mapping of Sn@C annealed at various temperatures.

The electrochemical testing results showed that Sn@C-500 achieved significant performance improvements compared to the other Sn@C samples and Super P, a commercial conductive additive. The Sn@C-500 sample exhibited a reversible capacity approximately 10% higher than Super P, maintaining 375 mAh g^{-1} after 200 cycles at a current density of 0.5 A g^{-1}. This increase in capacity is attributed to Sn's dual role as a conductive agent and lithium-alloying material, which contributed to enhanced lithium storage. Electrochemical impedance spectroscopy (EIS)

demonstrated that Sn@C-500 maintained a lower internal resistance over extended cycling, confirming its stability and effectiveness as a conductive network within the electrode. Additionally, the lower resistance facilitated faster charge transfer dynamics, contributing to overall capacity retention and stability during cycling.

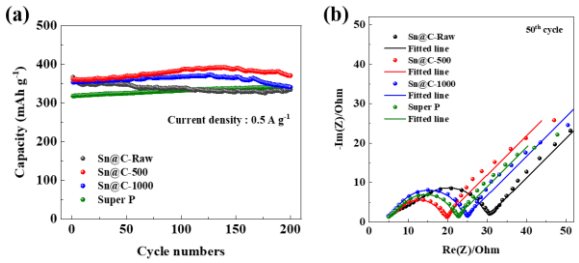

Fig. 2. (a) Cycling performance; and (b) Nyquist plot of Sn@C annealed at various temperatures and Super P.

Moreover, the durability of Sn@C-500 was examined through surface morphology analysis before and after cycling. SEM images taken after 100 and 200 cycles indicated minimal cracking or particle expansion, underscoring the mechanical stability imparted by the carbon matrix. The matrix structure of Sn@C-500 effectively buffered the volume expansion of Sn, ensuring long-term electrode stability and preventing capacity degradation often observed in traditional Sn-based anodes. The combined attributes of enhanced capacity, lower internal resistance, and stable morphology highlight Sn@C-500's potential as a bifunctional conductive additive that can contribute significantly to LIB energy density and cycle life.

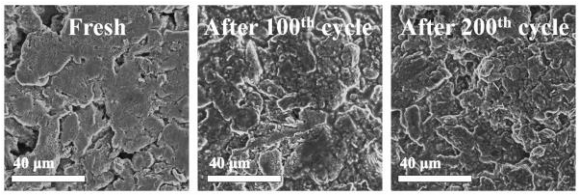

Fig. 3. SEM images of Sn@C-500 fresh, at 100th and 200th cycle.

3. CONCLUSION

This study successfully demonstrates that Sn@C-500, synthesized through plasma engineering, functions as a bifunctional additive, combining Sn's lithium alloying and conductive properties within a carbon matrix. The dual role of Sn in Sn@C-500 enabled both increased lithium storage and improved conductivity, addressing the limitations of traditional CB additives. The Sn@C-500 sample displayed enhanced reversible capacity and reduced internal resistance, positioning it as a highly effective "active" conductive additive for LIB anodes. This research provides insights into the potential of Sn-doped carbon materials to serve as advanced conductive additives for high-performance LIBs. By leveraging the synergy between active material incorporation and conductive enhancement, Sn@C composites can contribute to the next generation of energy-dense, stable, and efficient LIBs, paving the way for further exploration into composite conductive additives in battery technologies.

REFERENCES

1 G. Harper, R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, A. Walton, P. Christensen, O. Heidrich, S. Lambert, *nature*, 575 (2019) 75-86.

2 N. Nitta, F. Wu, J. T. Lee, G. Yushin, *Materials today*, 18 (2015) 252-264.

3 M. N. Obrovac, V. L. Chevrier, Chemical reviews, 114 (2014) 11444-11502.

4 G. Ma, W. Yang, C. Xu, S. Che, Y. Li, H. Liu, N. Chen, G. Zhang, H. Liu, N. Wu, Electrochimica Acta, 428 (2022) 140898.