

OPTIMIZING THE EFFICIENCY OF ELECTRIC VEHICLE BATTERIES VIA NIOBIUM DOPING - A REVIEW

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ABSTRACT

Electric vehicle (EV) batteries are a focal point of research due to the global shift toward sustainable energy and the demand for high-performance energy storage systems. Niobium (Nb) doping in electrode materials has emerged as a promising approach to improve battery performance across lithium-ion (Li-ion), sodium-ion (Na-ion), and next-generation technologies. Niobium has unique properties to enhance conductivity, cycling stability, charge/discharge rates, and mechanical robustness. By stabilizing crystal structures and increasing ion diffusion pathways, niobium reduces capacity fading and facilitates faster charging. Recent advancements highlight its role in improving energy density and thermal stability in Li-ion batteries, addressing structural challenges in Na-ion batteries, and enhancing compatibility in solid-state systems. Despite these benefits, challenges such as resource availability, cost, and scalability must be addressed to enable widespread adoption. Additionally, sustainability assessments and optimization of manufacturing processes are essential for its practical implementation. This review explores the mechanisms underlying niobium's impact, recent breakthroughs in niobium-doped materials, and future prospects for overcoming challenges. Niobium doping represents a viable pathway to advancing EV battery technologies, offering a sustainable solution for next-generation energy storage systems and contributing to the realization of a greener, electrified future.

Keywords: *Electric Vehicle, Li-ion batteries, Na-ion batteries, Niobium Doping, Energy storage*

1. INTRODUCTION

Recently, Li-ion batteries (LIBs) are extensively used in hand-held smartphones, electric vehicles (EVs) and hybrid electric vehicles (HEVs) owing to their superior specific capacity,

good cost-efficiency and better environmental sustainability [1,2]. As the foundation of electric vehicles (EVs), high-performance batteries are essential to this shift. Due to their high energy density, comparatively quick charge periods, and affordability, lithium-ion batteries (LIBs) currently dominate the EV market. Nevertheless, the increasing demand for EVs has highlighted the necessity of battery technology improvements to allow for reduced pricing, quicker charging, and longer driving ranges. Transition metal doping is a promising approach to enhancing battery performance. Niobium (Nb) and other transition metals have many advantages when it comes to altering the characteristics of electrodes. Because it can improve structural stability, decrease dendritic formation, boost cycling stability, and improve conductivity in a variety of battery materials, niobium in particular has drawn interest. Niobium doping's effects on lithium-ion, sodium-ion, and future battery systems are the main topic of this paper, which also gives a summary of recent developments, mechanisms of action, and difficulties in real-world implementation.

Beyond lithium-ion batteries, niobium doping exhibits great potential in sodium-ion and developing battery systems, where it can solve important issues including structural degradation and slower ionic diffusion. With an emphasis on its effects on lithium-ion, sodium-ion, and next-generation systems, this article seeks to present a thorough examination of niobium's contribution to the development of battery technology. This research aims to demonstrate the revolutionary potential of niobium doping in influencing the direction of sustainable energy storage by examining recent developments, clarifying the mechanisms of action, and tackling the difficulties related to its practical application.

2. NIOBIUM PROPERTIES FOR BATTERY PERFORMANCE

Niobium is a transition metal with unique properties that make it an attractive candidate for doping electrode materials. It is known for its high electrical conductivity, structural stability, and resistance to corrosion. Additionally, niobium's ability to engage in redox reactions enhances its compatibility with various electrochemical processes. Niobium has excellent electrical conductivity, which can boost the overall performance of battery materials, especially those that have low intrinsic conductivity, such as lithium iron phosphate (LiFePO_4) [3]. Niobium undergoes reversible redox reactions that facilitate the movement of ions during charge/discharge cycles, providing the electrochemical flexibility needed in batteries. It is highly stable under electrochemical cycling, making it ideal for enhancing the durability of battery electrodes [4]. Niobium is typically doped into battery materials either

by substituting metal atoms in the crystal lattice or by being incorporated in the form of niobium oxide (Nb_2O_5). These atoms help to increase the number of conduction paths within the material, thereby improving ionic conductivity. This is particularly beneficial for materials like LiFePO_4 or NaCoO_2 , which have low intrinsic conductivity [5]. It also improves the structural integrity of electrode materials during cycling, resulting in better cycling stability and preventing material degradation from repeated volume changes during charge/discharge cycles [6].

3. Niobium as a Dopant in Different Battery Materials

3.1 In Lithium Ion Batteries

Lithium-ion batteries (LIBs) are the dominant energy storage technology for electric vehicles, offering high energy density and efficiency. However, challenges such as low conductivity, limited rate capability, and poor cycle stability remain. Niobium doping has been investigated to address these challenges, particularly in cathode and anode materials. Niobium-doped cathodes exhibit enhanced power density, allowing for faster charging times without compromising energy capacity [7].

For increased utilization of $\text{LiNi}_{0.5}\text{Co}_{0.2}\text{Mn}_{0.3}\text{O}_2$ cathode, substantial issues such as low rate capability and short cycle life should be resolved. The controlled doping of Niobium (Nb) resulted in lowered impedance, expanded LiO_2 inter-slab space, and suppressed $\text{Li}^+/\text{Ni}^{2+}$ site exchange, which could help stabilize the structure and improve performance even at high temperatures [8]. The crystal structures of the as-prepared samples were analyzed by X-ray diffraction (XRD). The diffraction peaks of all the samples could be ascribed to layered hexagonal structure $\alpha\text{-NaFeO}_2$ with R-3m space group without any detectable impure peaks. The diffraction peaks at (006)/(102) and (108)/(110) were clearly split, which inferred that the Nb dopant would not affect the highly ordered layered structure. This is shown in figure 3.1.1.

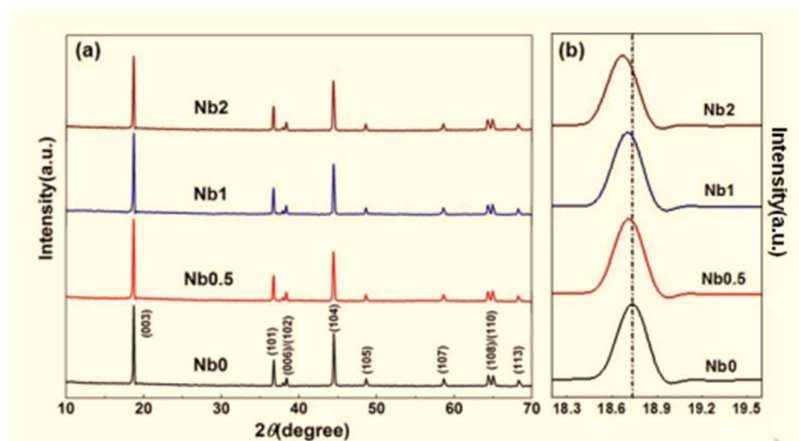


Figure 3.1.1 XRD patterns of bare (Nb0) and Nb-doped $\text{LiNi}_{0.5}\text{Co}_{0.2}\text{Mn}_{0.3}\text{O}_2$ (Nb0.5, Nb1, Nb2) (b) the magnified zone from 18.3 to 19.5° of XRD patterns.

The rate capabilities of all samples are shown in Figure 3.1.2. Charge–discharge tests were performed for five times under each current density. As the current density increased, the discharge specific capacity of sample Nb0 decreased rapidly. And the Nb1 sample exhibits the best rate performance. The discharge capacity of Nb1 at 5.0 C is 125.5 $\text{mAh}\cdot\text{g}^{-1}$, whereas those of Nb0, Nb0.005, and Nb2 are only 108.2, 117.0, and 113.2 $\text{mAh}\cdot\text{g}^{-1}$, respectively. All these results prove that an appropriate amount of Nb doping could adequately improve the rate capability.

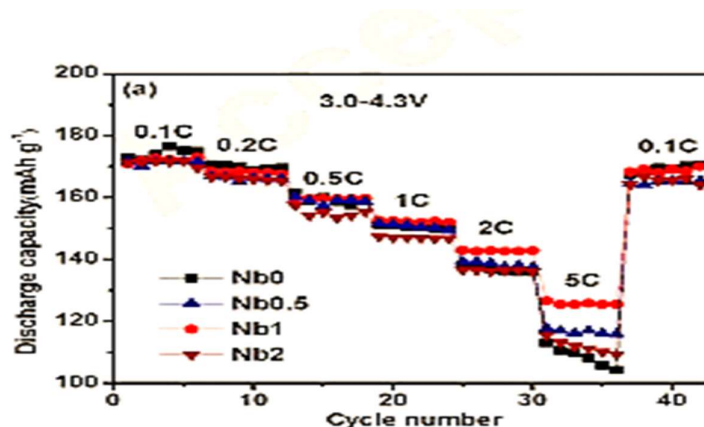


Figure 3.1.2 Rate performances of the prepared samples at different current densities.

Thus, an appropriate amount of Nb doping into $\text{LiNi}_{0.5}\text{Co}_{0.2}\text{Mn}_{0.3}\text{O}_2$ could improve its electrochemical performance, as well as promote the development of its industrialization.

3.2 Sodium Ion Batteries

Sodium-ion batteries (NIBs) are emerging as a promising alternative to lithium-ion batteries, primarily due to the abundant and cost-effective nature of sodium. However, NIBs face challenges with energy density and cycling stability. Niobium doping has shown promise in improving the performance of sodium-ion battery materials.

Niobium was used as a dopant in the high-temperature solid-phase technique for generating the cathode material P2- $\text{Na}_{0.75}\text{Co}_{0.20}\text{Mn}_{0.78}\text{Nb}_{0.02}\text{O}_2$. According to the research, doping with niobium widens the deintercalation channel for Na^+ ions and improves the overall electrochemical performance of the parent material by increasing the interlayer gap of the sodium layers. After 100 cycles, the oxide's initial discharge capacity at 0.1 C is 161.7 mAh g^{-1} , and it reaches 147.1 mAh g^{-1} with nearly no deterioration. Its capacity retention rate is 91.0%. Therefore, the metal element niobium can improve the electrochemical performance of sodium ion batteries [9]. The XRD spectra comparison and Rietveld refinement of NCM (Nickel Cobalt Manganese) and NCMN (Nickel Cobalt Manganese along with Niobium) are shown in Fig. 3.2

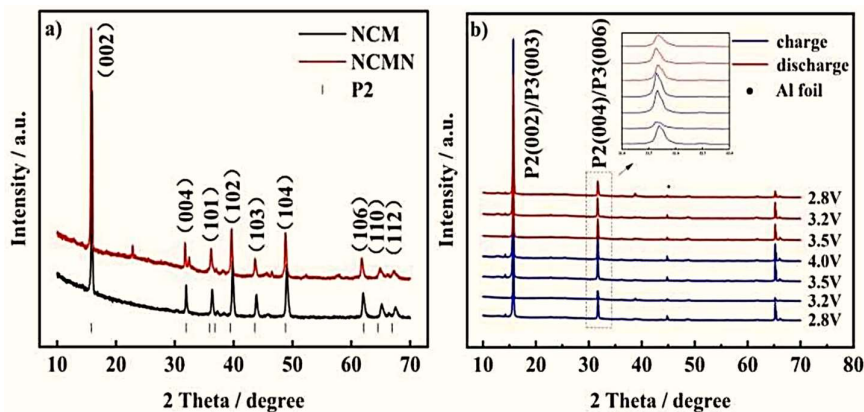


Figure 3.2 Rietveld refinement of NCM and NCMN

a) X-ray Diffraction (XRD) Patterns b) In-situ XRD During Charge-Discharge Cycling

The fact that all of the distinctive peaks before and after doping match P2 phase structures shows that the parent material's structure was unaffected by the Nb^{5+} doping. Additionally, the samples' crisp peak shape both before and after doping indicates good crystallinity. In Figure 3.2 (a) the presence of characteristic peaks indicates the crystalline structures of both materials. NCMN (red) exhibits sharper peaks, suggesting improved crystallinity and phase stability due to niobium doping. The indexed peaks correspond to

different lattice planes, with (002), (004), (101), (102), (103), (104), (106), and (112) reflections, showing the material's layered structure. In Figure 3.2 (b) the panel shows how the material structure evolves during electrochemical cycling. Different voltages (2.8V to 4.0V) are tested, with charge (blue) and discharge (red) processes analysed. Peak shifts during cycling indicate reversible structural changes, which affect battery stability.

4. Challenges and Limitations of Niobium Doping

Niobium is a relatively expensive material, and its scalability for large-scale battery production remains a challenge. Further research is needed to develop cost-effective methods for incorporating niobium into battery materials [10]. Niobium may react with other materials, such as electrolytes, leading to potential instability or performance degradation. Careful optimization of the doping process is necessary to ensure compatibility [11]. The long-term performance of niobium-doped materials under extreme cycling conditions (e.g., high temperatures, fast charge/discharge rates) needs further investigation to ensure that niobium does not cause any detrimental effects over time [12].

From an electrochemical perspective, niobium's poor electrical conductivity can increase internal resistance, reducing the rate capability of the battery. While it enhances thermal stability, it may slightly lower the specific capacity due to inactive Nb sites. Processing challenges also arise, as achieving uniform Nb incorporation requires precise and costly synthesis techniques. Furthermore, niobium may react with electrolyte components, affecting interfacial stability. Economically, niobium is expensive compared to conventional dopants like aluminum or magnesium, making large-scale production costly. Modifying existing manufacturing processes to accommodate Nb-doped materials further adds to expenses. Sustainability concerns also emerge due to the limited geographic availability of niobium, primarily sourced from Brazil and Canada, leading to potential supply chain risks. Additionally, the recycling of Nb-doped batteries requires specialized processes, which are not yet widely developed. Despite these limitations, ongoing research aims to optimize Nb doping levels and explore nanostructuring techniques to overcome these challenges and improve EV battery performance.

5. Conclusion

Niobium doping presents a promising strategy for enhancing the performance of electric vehicle (EV) batteries, offering significant improvements in conductivity, cycling stability, rate capability, and mechanical strength. In lithium-ion and sodium-ion batteries, niobium has demonstrated its ability to increase power density, reduce capacity fade, and enhance long-term cycling stability, making it an effective dopant for both cathodes and anodes. Its high ionic conductivity and structural stability contribute to improved charge-discharge efficiency and prolonged battery lifespan. Beyond conventional lithium-ion technology, niobium also shows potential in emerging battery systems such as solid-state and magnesium-ion batteries, where its unique electrochemical properties can enhance safety, energy density, and overall performance. These advantages make niobium a valuable candidate for next-generation energy storage solutions. Future research should focus on optimizing doping techniques, refining material compositions, and improving large-scale synthesis processes to enhance cost-effectiveness and commercial viability. Addressing challenges related to material availability and process scalability will be crucial for widespread adoption. With continued advancements, niobium doping could play a pivotal role in the development of high-performance, sustainable battery technologies, accelerating the transition toward cleaner, more efficient electric mobility and contributing to a greener energy future.

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