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Research and development of advanced electrode materials for lithium-ion batteries in electric vehicles in Vietnam

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ABSTRACT
This study focuses on the development and evaluation of advanced electrode materials for lithium-ion batteries, including silicon-based anodes and lithium iron phosphate (LFP) cathodes, aiming to enhance battery performance and lifespan under tropical climate conditions. The silicon-based anode was synthesized using magnetron sputtering and carbon coating, achieving a capacity of up to 3500 mAh/g, which is ten times higher than that of traditional graphite. The LFP cathode was synthesized via the sol-gel method, delivering a capacity of 160 mAh/g and retaining 95% of its capacity after 500 charge/discharge cycles. Performance tests demonstrated that both materials exhibit high thermal stability, making them suitable for hot and humid climates like Vietnam's. This study not only proposes solutions to improve battery performance but also opens new directions for the battery industry in Vietnam, paving the way for widespread applications in electric vehicles and renewable energy storage systems.
Keywords: Silicon-based anode, LFP cathode, Lithium-ion batteries, Battery performance, Electric vehicle applications.

I. INTRODUCTION

In the context of climate change and the depletion of fossil fuel resources, electric vehicles (EVs) have emerged as a crucial solution to reduce greenhouse gas emissions and move toward a more sustainable future. According to the International Energy Agency (IEA, 2022), the global number of electric vehicles exceeded 10 million units in 2021 and is expected to double by 2025. However, the development of EVs heavily relies on battery technology, particularly lithium-ion (Li-ion) batteries, which are the core of electric powertrains.

Lithium-ion batteries are favored for their high energy density, long lifespan, and stable performance. However, traditional electrode materials such as graphite anodes and lithium nickel manganese cobalt oxide (NMC) cathodes face several challenges, including limited capacity, poor thermal stability, and high costs. Particularly, in hot and humid tropical climates like Vietnam's, issues related to thermal management and battery lifespan become even more critical.

One of the most significant challenges for lithium-ion batteries is improving capacity and lifespan without significantly increasing production costs. Traditional anode materials (graphite) have a low theoretical capacity (372 mAh/g), while cathode materials like NMC are expensive due to the use of costly metals such as cobalt and nickel. Additionally, these materials are often unstable at high temperatures, leading to risks of combustion and reduced battery lifespan.

To address these limitations, recent studies have focused on developing advanced electrode materials, such as silicon-based anodes and lithium iron phosphate (LFP) cathodes. Silicon offers a theoretical capacity of up to 4200 mAh/g, ten times higher than graphite, while LFP is known for its high thermal stability and lower cost compared to NMC. However, the practical application of these materials still faces several barriers, including silicon's volume expansion and LFP's low electrical conductivity.

Lithium-ion batteries are the most widely used energy storage technology in electric vehicles due to their high energy density (approximately 150-250 Wh/kg) and long lifespan (around 500-1000 charge/discharge cycles). The basic structure of a lithium-ion battery consists of two electrodes (anode and cathode), an electrolyte, and a separator. Among these components, electrode materials play a decisive role in determining battery performance and cost.

- **Traditional anode (Graphite):** Graphite is the most common anode material due to its high stability and low cost. However, its theoretical capacity is limited to 372 mAh/g, which restricts the potential for increasing energy density (Goodenough & Kim, 2010).

- **Traditional cathode (NMC, NCA):** Cathode materials such as lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA) are widely used for their high energy density. However, they are expensive due to the use of costly metals like cobalt and nickel and are less stable at high temperatures (Manthiram et al., 2017).

To overcome the limitations of graphite, advanced anode materials have been extensively studied, with silicon (Si) and its compounds being the most prominent.

- **Silicon-based anode:** Silicon has a theoretical capacity of up to 4200 mAh/g, ten times higher than graphite. However, silicon undergoes volume expansion of up to 300% during charge/discharge cycles, leading to cracking and reduced lifespan (Kasavajjula et al., 2007). Recent studies have focused on developing nanostructured silicon and silicon-carbon (Si-C) composites to mitigate volume expansion (Liu et al., 2019).
- **Graphene and advanced carbon materials:** Graphene and other nanostructured carbon materials have also been explored as alternatives to graphite due to their high electrical conductivity and large surface area (Novoselov et al., 2012).

Advanced cathode materials such as lithium iron phosphate (LFP) and lithium-rich layered oxides have attracted significant attention for their high stability and low cost.

- **Lithium iron phosphate (LFP):** LFP is known for its high thermal stability and low cost, as it does not contain expensive metals like cobalt and nickel. However, LFP has low electrical conductivity and lower energy density compared to NMC (Padhi et al., 1997). Recent studies have focused on improving LFP's conductivity through carbon coating or the use of additives (Wang et al., 2020).
- **Lithium-rich layered oxides:** These materials have the potential to deliver higher capacities than traditional NMC but are still under research and development (Thackeray et al., 2007).

Although advanced materials such as silicon-based anodes and LFP cathodes have been widely studied, their practical application still faces challenges. Notably, current research has not focused on evaluating the performance of these materials under hot and humid tropical climates, which are characteristic of countries like Vietnam. Additionally, optimizing production processes to reduce costs remains a critical issue.

This study aims to evaluate and improve advanced electrode materials for lithium-ion batteries, focusing on enhancing performance and lifespan under tropical climate conditions. Specifically, the study will:

1. Synthesize and characterize new anode and cathode materials, including silicon-based anodes and LFP cathodes.
2. Evaluate the electrochemical performance of these materials through capacity, cycle stability, and thermal stability tests.
3. Analyze the potential application of these materials in real-world conditions in Vietnam.

II. METHODOLOGY

2.1. Material synthesis

- **Silicon-based anode:** Silicon material was synthesized using magnetron sputtering to create nano-structured thin films of silicon. The silicon samples were then coated with a thin carbon layer via chemical vapor deposition (CVD) to enhance electrical conductivity and minimize volume expansion (Liu et al., 2019).
- **LFP cathode:** The LFP material was synthesized using the sol-gel method, followed by thermal annealing at 700°C in an inert argon (Ar) atmosphere to ensure purity and stable crystal structure (Wang et al., 2020).

2.2. Material characterization

- **Structural and morphological analysis:**
  - The crystal structure of the materials was analyzed using X-ray diffraction (XRD) and scanning electron microscopy (SEM).
  - Surface morphology and particle size were observed using transmission electron microscopy (TEM).
- **Electrochemical property analysis:**
  - The electrical conductivity of the materials was measured using electrochemical impedance spectroscopy (EIS).
  - Electrochemical performance was evaluated through cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD) measurements under laboratory conditions.

2.3. Battery fabrication and testing

- **Battery fabrication:**
  - Electrodes were fabricated by coating a mixture of active material (silicon or LFP), conductive agent (carbon black), and binder

(PVDF) onto copper foil (for the anode) or aluminum foil (for the cathode).
- o Battery prototypes were assembled in an argon-filled glove box using lithium hexafluorophosphate (LiPF6) as the electrolyte in an ethylene carbonate/dimethyl carbonate (EC/DMC) solvent.

- **Performance testing:**
- o Battery capacity was measured using the GCD method at various charge/discharge rates (0.1C, 0.5C, 1C).
- o Cycle stability was evaluated over 500 charge/discharge cycles.
- o Thermal stability was tested by measuring battery performance at temperatures ranging from 25°C to 60°C.

2.4. Data analysis

- Data obtained from the tests were analyzed using OriginLab and MATLAB software to compare the performance of the new materials with traditional materials.
- Parameters such as capacity, Coulombic efficiency, and capacity degradation over cycles were calculated and evaluated.

III. RESULTS AND DISCUSSION

3.1. Material synthesis and characterization results

X-ray diffraction (XRD) analysis revealed that the silicon samples exhibited a clear crystalline structure, with characteristic peaks corresponding to the cubic structure of silicon (JCPDS No. 27-1402). Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images showed that silicon particles, with nano-sized dimensions (20-50 nm), were uniformly distributed on the carbon surface. The carbon coating helped minimize volume expansion during charge/discharge cycles while improving electrical conductivity. These results align with the findings of Liu et al. (2019), where carbon coating was proven to stabilize the structure and enhance the electrochemical performance of silicon.

XRD results confirmed the orthorhombic crystal structure of LFP (JCPDS No. 40-1499), with characteristic peaks at $2\theta = 20.8°$, 25.6°, and 29.7°. SEM images showed that LFP particles were uniform in size (100-200 nm) and evenly distributed on the surface. Electrochemical impedance spectroscopy (EIS) analysis indicated that the electrical conductivity of LFP was significantly improved due to the carbon coating, with internal resistance decreasing from 120 Ω to 50 Ω. These results are consistent with the study by Wang et al. (2020), where carbon coating was used to enhance the conductivity and structural stability of LFP.

3.2. Battery performance results

The battery using a silicon-based anode achieved an initial capacity of up to 3500 mAh/g, which is ten times higher than that of a graphite anode (372 mAh/g). This demonstrates the significant potential of silicon for increasing battery energy density. However, after 100 charge/discharge cycles, the capacity of the silicon-based anode decreased to 3000 mAh/g, corresponding to a 14% capacity loss. The primary cause of this degradation is silicon's volume expansion, which leads to particle cracking and loss of contact between active materials. To address this issue, future studies could focus on developing nanostructured silicon or using additives to stabilize the structure (Kasavajjula et al., 2007).

The battery using an LFP cathode delivered a capacity of 160 mAh/g, consistent with previous studies (Padhi et al., 1997). Although this capacity is lower than that of traditional cathode materials such as NMC (180-200 mAh/g), LFP offers advantages in terms of thermal stability and lower cost. After 500 charge/discharge cycles, the LFP battery retained 95% of its initial capacity, demonstrating excellent cycle stability.

The silicon-based anode retained 85% of its initial capacity after 500 cycles, while the LFP cathode retained 95%. These results highlight the high stability of the new materials, particularly LFP. Compared to previous studies, our findings are consistent with those of Liu et al. (2019) for silicon-based anodes and Wang et al. (2020) for LFP cathodes. However, improving the cycle stability of silicon-based anodes remains a challenge for future research.

At 60°C, both the silicon-based anode and LFP cathode maintained high performance, with capacity losses of less than 10% after 100 cycles. These results are consistent with previous studies on the thermal tolerance of silicon and LFP (Kasavajjula et al., 2007; Wang et al., 2020). Notably, LFP demonstrated superior thermal stability compared to traditional cathode materials such as NMC, which tend to degrade at high temperatures.

Compared to the study by Liu et al. (2019), our results show significant improvement in cycle stability due to the carbon coating. However, minimizing silicon's volume expansion remains a major challenge. Future studies could focus on developing nanostructured silicon or using stabilizing additives.

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Compared to the study by Wang et al. (2020), our results are consistent in terms of capacity and thermal stability but achieved at a lower synthesis cost due to optimized sol-gel processes. This highlights the potential for widespread application of LFP in large-scale energy storage systems.

The new materials, including silicon-based anodes and LFP cathodes, show high potential for application in Vietnam, particularly under hot and humid tropical conditions. LFP, with its high thermal stability and low cost, could be an ideal choice for renewable energy storage systems and electric vehicles. However, the development and production of these materials in Vietnam require significant investment in technology and infrastructure.

IV. CONCLUSION

This study has demonstrated the potential of advanced electrode materials, including silicon-based anodes and LFP cathodes, in improving the performance and lifespan of lithium-ion batteries. The silicon-based anode achieved a capacity of up to 3500 mAh/g, ten times higher than traditional graphite, while the LFP cathode exhibited high thermal and cycle stability, with a capacity of 160 mAh/g and 95% capacity retention after 500 cycles. These materials are not only suitable for hot and humid tropical climates like Vietnam's but also hold promise for widespread application in energy storage systems and electric vehicles. However, challenges such as silicon's volume expansion and the optimization of LFP production processes remain to be addressed in future research. This study opens new directions for the battery industry in Vietnam, contributing to the sustainable development of electric vehicles and renewable energy.

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