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Hairus Abdullah

# Vanadium Oxide-Based Cathode for Supercapacitor Applications

## Using Electrodeposition Method

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# Preface

Energy crisis and environmental issues are the most crucial topics in recent years. Non-renewable fossil fuels not only bring ecological problems, but also impact the global economy and society. Implementing solar cell technology has been the solution to overcome environmental issues. However, the intermittent of sunlight poses a significant challenge in harnessing the solar light energy. Technological development of energy storage materials in supercapacitors and batteries is one of the crucial tasks to support the use of green energy sources. An immediate need exists for energy storage devices that are not only efficient but also environmentally sustainable. These devices should be capable of supplying power to energy-intensive sectors, including transportation and portable gadgets, for example, laptops, camcorders, mobile phones, electric vehicles, and hybrid electric vehicles. The devices such as fuel cells, solar cells, photoelectrochemical water splitting cells, batteries (particularly Li-ion batteries), and supercapacitors are typical energy storage technologies. The functionality of these energy devices is substantially influenced by the characteristics of nanostructured materials. It is hypothesized that advancements in nanomaterial chemistry may provide the means to achieve additional breakthroughs in energy storage systems. Owing to the large surface-to-volume ratios, favorable transport properties, altered physical properties, and confinement effects resulting from their nanoscale dimensions. Therefore, nanostructured materials have been the subject of extensive research. Vanadium-based electrode emerges as a promising energy material. The vanadium electron configuration is $3d^3$ $4s^2$ and all five valence electrons in bonding processes result in the formation of multivalent V, ranging from $V^{2+}$ to $V^{5+}$. This multivalent V contributes to the formation of vanadium oxides, vanadates, and vanadium phosphates. In addition to the abundant source and rich electrochemical characteristics of V ($V^{2+}$ to $V^{5+}$), V-based nanomaterials are also economically viable and a promising electrode candidate in the field of energy storage.

In this book, the related backgrounds of supercapacitors and the basic indicators to examine supercapacitor performances are briefly discussed in Chap. 1. Further state of art works in developing supercapacitors is provided in Chap. 2. Some fundamental regulations for improving the electrochemical properties are also discussed in the chapter. An example of a typical work of vanadium oxide-based cathode for a supercapacitor prepared by an electrodeposition method is provided in Chap. 3. A further advanced improvement of electrodeposited vanadium oxide supercapacitor with bilayer $Ni(OH)_2/VO_x$ is demonstrated in Chap. 4. In addition, Chap. 5 provides the advances of vanadium oxide supercapacitor works are discussed by providing different phases of $VO_x$ with various morphologies to extend and develop the V-based supercapacitor works. Finally, the author acknowledges Program Lembaga Penelitian/Pengabdian Masyarakat (LPPM), Universitas Prima Indonesia with grant number #43/PL/2024 dated 23rd January 2024 in supporting the present work.

Taipei, Taiwan Hairus Abdullah

# Contents

# Abbreviations

| | |
|---|---|
| AC | Active carbon |
| CNT | Carbon nanotube |
| CPE | Constant-phase element |
| Cs | Specific capacitance |
| CV | Cyclic voltammogram |
| DRS | Diffuse reflectance spectroscopy |
| EDLC | Electrostatic double-layer capacitor |
| EIS | Electrochemical impedance spectroscopy |
| FE-SEM | Field emission-scanning electron microscopy |
| GCD | Galvanostatic charge-discharge |
| HCP | Hexagonal closed-packed |
| HER | Hydrogen evolution reaction |
| $K_B$ | Boltzmann constant |
| LED | Light emitting diode |
| MO | Metal oxide |
| MWCNT | Multi-walled carbon nanotube |
| PANI | Polyaniline |
| PEDOT | Poly(3,4-ethylenedioxythiophene) |
| PPy | Polypyrrole |
| PVA | Polyvinyl alcohol |
| Rct | Charge transfer resistance |
| Rs | Internal series resistance |
| Rt | Tandem resistance |
| SAED | Selected area electron diffraction |
| SC | Supercapacitor |
| TEM | Transmission electron microscopy |
| TMO | Transition metal oxide |
| VN | Ni-doped vanadium cathode |
| XPS | X-Ray photoelectron spectroscopy |
| XRD | X-ray diffraction |

# Chapter 1
# Introduction

## 1.1 Backgrounds

The advancement of science and technology in recent years with 5G technology has indeed affected the development of society. However, highly efficient technology has increased the demand for energy consumption by pursuing more functions in applications. Therefore, energy supply components on devices are receiving more and more attention. Consistently, developing energy storage components becomes crucial to support advanced technology. In addition, energy storage components should have high energy density, fast charge and discharge, and long lifetime [1]. In order to comply with the above requirements, the development of supercapacitors was initiated. Supercapacitors are widely used in energy supply, vehicle transportation, mobile communications, marine transportation, national defense, and military fields. Generally, energy storage components are mainly batteries and traditional capacitors. Batteries have high energy density, but traditional capacitors have high power density, and supercapacitors have the characteristics of both traditional capacitors and batteries. Supercapacitor (SC), also known as electrochemical capacitor [2], has a higher capacitance than traditional capacitors due to its special energy storage mechanism. In addition, as the charge accumulates on the surface of electrodes, SC has a higher power density and faster charge and discharge process compared to batteries. SC has not only reversible characteristics similar to capacitors, but also a longer cycle life than batteries. Traditional capacitors have the advantages of high power density, fast charge and discharge, and long lifetime, but they have the disadvantages of low energy density. On the other hand, batteries have high energy density but low power density, long charge and discharge time, and poor cycle life. Supercapacitors have the advantages of high energy density, high power density, fast charge and discharge, and long cycle life. A specific Ragone plot can be seen in Fig. 1.1 [3].

Although supercapacitors have many advantages, they are still in the research stage. At this stage, most use the solvothermal synthesis method to fabricate active materials [4]. However, this method is unsuitable for mass manufacture, making its



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