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RECENT TRENDS IN RESEARCH IN CHEMICAL SCIENCES

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RECENT PROGRESS IN VANADIUM OXIDES AND THEIR COMPOSITE AS ELECTRODE IN SUPERCAPACITOR APPLICATIONS

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ABSTRACT

Electricity is vital for progress, but reliance on non-renewable sources harms the environment and depletes resources. Solar energy offers promise but needs nighttime storage solutions. Supercapacitors, especially those using vanadium, are emerging as eco-friendly and cost-effective alternatives to traditional batteries. This chapter explores advancements in vanadium-based supercapacitors, emphasizing their potential for sustainable energy storage. A review discusses the appeal of vanadium-based nanostructured materials and composites for supercapacitor electrodes due to their unique properties. It covers recent research, electrochemical performance in various conditions, and future challenges and prospects for these materials in supercapacitor applications.

Keywords: Vanadium, Nanostructured, Supercapacitor, Electrochemistry, Energy density, etc.

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1. INTRODUCTION

Electricity stands as an indispensable necessity for humanity, catalyzing societal progress and modernization. Nevertheless, our heavy reliance on non-renewable energy sources for electricity generation has raised environmental concerns, with pollution becoming a looming threat. Equally concerning is the fact that these non-renewable resources are rapidly dwindling[1]. Consequently, the contemporary era has witnessed a monumental shift towards exploring and showcasing novel energy production systems. One noteworthy avenue in this pursuit is the harnessing of solar energy, which, although pivotal, introduces a pressing challenge – nighttime energy generation and storage[2].

Addressing this challenge necessitates a profound consideration of energy storage solutions. Among the contenders in this arena are lead-acid batteries, lithium-ion batteries (LiB), and supercapacitors. While lead-acid batteries have historically played a prominent role, their toxicity has raised concerns. Similarly, the high costs associated with LiB have spurred the search for alternative energy storage systems. Enter supercapacitors, emerging as frontrunners due to their promising attributes. Distinctively, supercapacitors have gained significant traction for their unique properties, offering a compelling alternative to conventional batteries. A shining prospect in this context is the utilization of vanadium, a low-cost, non-polluting, and non-precious metal element. Vanadium's various oxides, hydroxides, and sulphides can be synthesized into diverse structures and morphologies, making it a prime candidate for advanced supercapacitor (Scp) development[3,4]. This chapter delves into the latest advancements within the realm of vanadium-based supercapacitors. It meticulously explores the influence of different morphologies of vanadium-based oxides, hydroxides, and sulphides on Scp performance. By examining these intricacies, we seek to shed light on the promising prospects of vanadium-based supercapacitors. In an age where sustainable energy storage is of paramount importance, the journey towards a greener and more efficient future takes an exciting turn with vanadium at its core [5]. The vanadium based nanostructured material and their composites have gained tremendous attraction because of their unique physical and chemical properties and wide applications as electrodes for Scp [6,7]. In this review, the latest research progress of vanadium based nanostructured material and their composites as an electrode material for Scp is introduced and discussed. Also, the recent development of vanadium based nanostructured material and their composites Scp in regards with their electrochemical performance in solid and liquid electrolyte, high specific capacitance (SC), high energy density and cycle life have been discussed in detail. Finally, the critical challenges and perspectives obligatory to be addressed for the future development of vanadium based nanostructured material and their composites for Scp applications are presented.

2. SUPERCAPACITOR

By ever-increasing demands of energy and excessive use of fossil fuel, the world mostly focused on development of renewable energy resources such as wind and solar power. In addition, to fulfill the present energy demand, the storage of generated electrical energy and its proper distribution has an equal importance. At present, lead acid batteries, the lithium-ion battery and supercapacitors are the major electrical energy storage devices. Based on the power (PD) and energy density (ED)of these energy storage devices each one has their own identity and scope of applications. The Figure 1 is the Ragon plot demonstrates the present status of specific energy (ED) with respect to the specific power (power density). The PD refers to how quickly a device can discharge its energy, while ED refers to how much energy a device contain [8–10].

Energy storage devices having high power release the amount of stored energy in a very short time interval, whereas energy devices with high ED releases the amount of energy in a long duration of time. For example, electrolytic and ceramic capacitors have a very high PD and lower ED. Batteries have high ED but lower PD. Considering the advantages and shortcoming of conventional capacitors and batteries, the Scp is one of the emerging energy storage devices which shows high PD and moderate ED [8,11–13].

In electrical devices, the high ED and high PD has a special importance. The traditional capacitors including electrolytic capacitor and ceramic capacitors demonstrated high PD whereas lead acid battery and lithium ion battery shows the high ED. Scp is an important energy storage device which comprises high PD and moderate energy density. Nowadays, due to the environmentally friendly nature and low cost of supercapacitors, it is gaining much interest as energy storage over the lead acid and LiB. The Scp is an important energy storage device which comprises high PD and moderate energy density[1,8]. Also, it bridges the gap between battery and capacitor. However, low ED and low cycle life are the major challenges amongst commercialization and complete replacement of established energy storage devices in today's market. Therefore, from many years, over the globe, many groups of electrochemical scientists continuously work on improvement of the ED of supercapacitors.

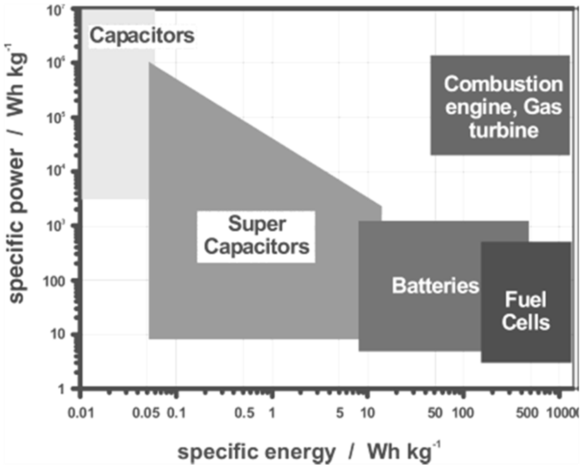

Figure 1. Ragon plot for different energy storage devices. Reproduce with the permission [14], Copyright 2004, American Chemical Society.

3. VANADIUM BASED SUPERCAPACITORS

The electrode and electrolyte are the heart of the supercapacitor. In supercapacitors, for the fabrication of electrode the active material, binder and substrate are the major components which decide the ED and cycle life of supercapacitor. The various transition oxides, carbon based materials and polymer are the highly utilized materials as active material for fabrication of electrodes for supercapacitor. Recently, many advanced materials such as metal organic framework (MOF), graphene, different layers transition metal oxides, Mxenes, etc. are demonstrated to be superior electrochemical activities in solid as well as liquid electrolytes, and resulted as excellent electrode material for supercapacitor. The electrode and electrolyte are the heart of supercapacitors. In supercapacitors, for the fabrication of electrodes the active material, binder and substrate are the major components which decide the ED and cycle life of a supercapacitor. The various transition oxides, carbon-based materials and polymer are the highly utilized materials as active material for fabrication of electrodes for supercapacitors. Recently, many advanced materials such as metal organic framework (MOF), graphene, different layers transition metal oxides, Mxenes, etc. are demonstrated to be superior electrochemical activities in solid as well as liquid electrolytes, and resulted as excellent electrode material for supercapacitor [2,15,16]. However, their high cost and difficulties in synthesis limits its applicability as electrode in supercapacitor.

The transition metals are low cost, environmentally friendly, and their oxides are easy to synthesize. Also, the different oxidation states of transition metals are one of the boons for synthesis of different binary as well as ternary metal oxide. Out of the different transition metal oxides, the vanadium metal is abundant in nature, environmentally friendly in nature and has different oxidation states. The different vanadium based oxides such VO, VO_2, V_2O_3, V_2O_5, etc, and their composites with carbon based material and polymers have been widely utilized as electrode material for supercapacitors [9,11,17,18]. Table .1 demonstrates the recent advancement concerning their energy density, SC and cycle life.

Table 1: Recent advancement of vanadium-based Scp

Sr. No	Material	Method of synthesis	Electrolyte	Potential window (V)	High SC ($F{\cdot}g^{-1}$), Current density/ Scan rate	ED ($Whkg^{-1}$)	Retention , Cycle	Year, [Ref.]
1	Ammonium vanadium oxide	Hydrothermal	1 M NH_4Cl/ PVA	0.8 -1.0	339, 1 $mA{\cdot}cm^{-2}$	15.9	71%, 14,000	2022, [18]
2	Nickel oxide/ vanadium oxide/ reduced graphene oxide	Hydrothermal	1 M KCl	0.0-0.8	1265.5 Fg^{-1}, 5 mVs^{-1}	41.4	92.2%, 4000	2022, [19]
3	V2O5/reduced graphene oxide	Hydrothermal	1 M Na_2SO_4	− 0.1–0.9	468.5 Fg^{-1}, 1 A g^{-1}	29.5	92.3%, 10,000	2022, [20]
4	$CeVO_4$/Ppy	Hydrothermal	1 M KOH	-0.1 to 0.4	1236 Fg^{-1}, 0.75 Ag^{-1}	52.2	92.6%, 10,000	2021, [11]
5	Sulfur doped $Co_3V_2O_8$	Hydrothermal	6 M KOH	−0.2 to 0.50	410 $mAhg^{-1}$, 2 Ag^{-1}.	36.4	94.2%, 4000	2021, [21]
	MnO_2/V2O5/ rGO	electrodeposition	1 M KCl	0-0.8	1403.5 F/g, 5 mV/cm^{-2}	60.4	90.3%, 5000	2021, [22]
6.	V_2O_5/carbon nanotubes	--	1 M Na_2SO_4	-1.1–0	284 F g^{-1}, 2 A g^{-1}	32.3	76%, 5000	2021, [3]
7.	V_2O_5 on carbon fiber cloth	Electrodeposition	1 M Na_2SO_4	0-1.8	354 mF/cm^2, 1 mA/cm^2	13	94%, 10,000	2021, [1]
8	Brookite phase VO_2	Chemical bath deposition	5 M LiCl	-0.2-0.8	1248 mF/cm^{-2}, 1 mA/cm^2	36.3	83.3%, 6000, at 10 $mAcm^{-2}$.	2022, [6]
9.	VOOH.	Hydrothermal	1 mol L^{-1} Li ClO_4/propylene carbonate	-0.4-0.5	323 F g^{-1}, 0.2 A g^{-1}	36.3,	70%, 2000, at 2 A g^{-1}.	202, [23]
10.	V_6O_{13}@C	Sol-hydrothermal method	1.0 M Na_2SO_4	0-0.8	545 F g^{-1}, 0.5 A g^{-1}	8.9	88.3%, 2000 at 0.5 A g^{-1}	2020, [13]

4. CONCLUSION AND FUTURE PROSPECTIVE

This article describes progress of different vanadium-based oxides and their electrochemical performance as electrode material for supercapacitors. Due to the low cost and environmentally friendly nature of the vanadium metal oxides, the vanadium oxides and its different composites have been excessively studied in supercapacitors as the electrode material. As compared to the other transition metal oxide-based supercapacitors, the energy density and cycle life of the vanadium oxide-based supercapacitors is satisfactory. However, the low electrical conductivity and structural instability limit its electrochemical performance. To commercialize the vanadium oxide-based super-capacitors, its energy density and cycle life needs to improve. Therefore, the different materials such as carbon nanotubes, conducting polymers, reduced graphene oxides etc. should be used with vanadium-based nanostructures, and need to study in different solid and liquid electrolytes. Finally, we hope that these various research efforts will definitely result in a good electrode material for sustainable energy storage and recent energy needs.

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