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Facile fabrication of Ag-doped NiO nanostructures as a potential electrode material for enhanced supercapacitor applications

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ABSTRACT

Nickel oxide-based nanoparticles have emerged as promising pseudocapacitive electrode compounds for energy storage applications due to their affordability, distinct redox activity, and flexibility in tuning their microstructures through controlled synthesis techniques and doping mechanisms. In this present work, silver (Ag) doped NiO nanomaterials were successfully synthesized using the sol–gel technique and applied as electrode material for the supercapacitors, achieving high pseudocapacitive performance. The properties of the as-prepared electrode materials were investigated using various characteristic techniques. The X-ray diffraction (XRD) analysis reinforced the sample's purity and phase, with no secondary phase detected. In addition, as NiO concentration increased, the average crystallite size of the nanocomposites decreased from 13.79 to 5.34 nm as the concentration of Ag increased.The surface morphological investigations confirmed the spherical nanostructured compounds and the elemental distribution of the prepared sample, respectively. Electrochemical assessments were carried out in a three-electrode configuration via cyclic voltammetry (CV), galvanostatic charging–discharging (GCD), and electrochemical impedance spectroscopy (EIS) in a 2 M KOH electrolyte solution. The specific capacitance (C_{sp}) of the as-fabricated electrode samples with varied dopant (Ag) concentrations was examined at different scan rates of 5 to 200 mV/s. The specific capacitance (C_{sp}) of the Ag-doped NiO_{1-x} electrode with $x = 10\%$ was significantly higher (662 F/g) at a current density of 1 A/g, compared to other electrodes. Additionally, the Ag-doped NiO electrode demonstrated an energy density of 33.1 Wh/kg and a power density of 969 kW/kg. These results indicate that the fabricated nanostructures, particularly with Ag doping, are promising candidates for enhancing energy storage applications.

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1 Introduction

Owing to their sustainability and low environmental effect, alternative energy sources like solar and wind power have seen a global shift in favor in recent decades. Advanced energy storage and conversion technologies are crucial to harness these renewable sources effectively [1, 2]. Lithium-ion batteries (LIBs), supercapacitors, water splitting, CO_2 reduction, and fuel cells are notable developments in the field [3]. For instance, LIBs benefit from electrodes with superior charge capacity and longevity, while supercapacitors leverage nanostructured electrodes to achieve high power density and rapid charge–discharge cycles. Water splitting and CO_2 reduction technologies demand catalysts with exceptional activity and stability to facilitate efficient reactions [3, 4]. Effective energy conversion and storage technologies require electrode materials with adequate endurance, a larger surface area, and a significant amount of activity. The application is what determines how well these materials work. Different types of materials have been examined for use as supercapacitors' electrode materials, as well as for use as catalysts in water splitting for the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) [5–7].

The growing need for sustainable energy solutions has intensified research into renewable energy generation, electrification of transportation systems, and adoption of digital technologies [8]. Supercapacitors have emerged as an important opportunity among various energy storage technologies, due to their exceptional power density, compact size, extended lifespan, broad operating temperatures, and rapid charge–discharge capabilities [9]. Supercapacitors, also known as ultracapacitors or electrochemical capacitors, are particularly notable for their ability to store and release large amounts of electrical energy through separation of charges between the surface of nanostructured electrodes and the electrolyte [10]. These breakthroughs in supercapacitor technology have the potential to drastically reduce reliance on fossil fuels while also mitigating environmental concerns, resulting in a more sustainable future. Furthermore, optimizing materials and structures for these technologies is crucial to improving performance, efficiency, and durability. Supercapacitors have various applications, including automotive, portable electronics, aerospace, and military. In automobiles, they improve regenerative braking, start-stop systems, and battery capacity [11]. Supercapacitors can be divided into three types based on the way they store energy: non-faradic electrochemical double-layer capacitors (EDLCs), faradic pseudo capacitors that involve redox reactions, and hybrid capacitors that combine a faradic and non-faradic electrode [12].

Transition metal oxides (TMO) NPs catch all-encompassing biological and non-biological applications owing to their physiochemical, electromagnetic and optical attributes, various morphology, structure profile, size, different crystalline phases, and the high surface–volume ratio [13]. Among numerous MOs (RuO_2, ZnO, NiO, MnO_2, and TiO_2, etc.), nickel oxide (NiO) has gained attractive attention because of its cost-effectiveness, abundance, well-defined sustainable electrochemical, magnetic, and catalytic properties, antioxidant, high thermo-chemical stability, tunable bandgap, excellent pseudocapacitive behavior, ease of synthesis, less toxicity, and environmental impact [14]. Additionally, NiONPs functions as a photoanode in dye-sensitized solar cells (DSSC) and lithium-ion batteries, as an electrode in supercapacitors in electrochemical performances and catalytic activities [14, 15].

Silver (Ag) and nickel oxide (NiO) are materials of significant interest in the field of energy storage, particularly for supercapacitor applications. [16]. Notably, NiO exhibits a high specific capacitance of 2584 F/g, highlighting its potential in energy storage devices such as supercapacitors. However, the performance of NiO-based electrodes can be further enhanced through doping with various elements [17]. Silver (Ag) doping in NiO has emerged as a promising approach to improve the electrochemical properties of NiO electrodes, particularly for applications in supercapacitors and other energy storage devices [18, 19]. Interestingly, incorporating Ag into NiO structures has shown improved specific capacitance and cycling stability, as evidenced by the synthesis of Ag-doped NiO porous networks and Ag/NiO nanocomposites [20]. Moreover, the existence of Ag can influence the structural and magnetic properties of NiO, as well as introduce antibacterial and photocatalytic functionalities [21].

Interestingly, while Ag doping generally improves the electrochemical properties of NiO, the synthesis methods and the resulting structures of Ag-doped NiO vary across studies. For instance, a porous network structure of Ag-doped NiO grown on Ni foam showed a specific capacitance of 570.7 F $g-1$ [22], whereas a ternary nanocomposite of Ag nanoparticles