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Stable neodymium gallium oxide ($Nd_3Ga_5O_{12}$ and Nd_3GaO_6) phases: a study on their asymmetric supercapacitor applications†

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Rare-earth-based nanomaterials with exceptional electrochemical properties can be obtained *via* a simple, low-cost, environment-friendly citrate–gel–matrix approach. Owing to their high specific capacitance, strong conductivity, and electrochemical stability, gallium-based materials are capable of withstanding numerous charge–discharge cycles, thus extending the life cycle of a supercapacitor. This tunability enabled researchers to alter the morphology and composition of the electrode to enhance supercapacitor performance. This research describes the investigation of stable neodymium gallium oxides, namely, $Nd_3Ga_5O_{12}$ and Nd_3GaO_6, synthesised *via* a citrate–gel–matrix method for asymmetric supercapacitor applications. Structural, morphological and optical studies elucidated the outstanding supercapacitor performance of $Nd_3Ga_5O_{12}$ and Nd_3GaO_6. XRD revealed the formation of cubic $Nd_3Ga_5O_{12}$ and orthorhombic Nd_3GaO_6. The vibrational modes, optical properties, surface morphology and oxidation states of $Nd_3Ga_xO_y$ phases were examined using Raman spectroscopy, UV–visible spectroscopy, scanning electron microscopy and X-ray photoelectron spectroscopy, respectively. Electrochemical studies using cyclic voltammetry, galvanostatic charge–discharge and electrochemical impedance spectroscopy revealed that the fabricated $Nd_3Ga_5O_{12}$ electrode resulted in a greater specific capacitance of about 418 F g^{-1} than Nd_3GaO_6, thereby displaying superior electrochemical characteristics. An asymmetric device fabricated with $Nd_3Ga_5O_{12}$ demonstrated a specific capacitance of about 64 F g^{-1}, energy density of 20 W h kg^{-1} and a power density of about 750 W kg^{-1}. Thus, the favorable attributes of $Nd_3Ga_xO_y$ in terms of its electrochemical performance indicate its significant promise for potential application in energy-storage devices.

1. Introduction

The emergence of rapid technical development has increased the demand for multifunctional applications. The fascinating features of nanoscale materials, including their size, shape, structural stabilities, and notable spatial homogeneity, have opened up several possibilities in technological applications.[1] The increasing quest for industrialization has prompted the need for low-toxicity, ecofriendly nanomaterials. Rare earth-related nanomaterials have been utilized by researchers since the 1960s in various fields, ranging from fuel cell electrodes, luminescent materials, electronic displays and permanent magnetic and catalytic materials to medical diagnostics, *etc*.

Rare earth-based nanomaterials also display outstanding electrochemical capabilities through multi-energy level transitions, and they are frequently used in electrochemical-based domains. Rare earth elements possess 4f electron sub-shells, which favor numerous possibilities for electron transition.[2] Similarly, research on rare-earth oxide garnets and nanogarnets has steadily increased in the past decades because of their significant attributes.[3] Gallium garnets are ideal for scintillator and laser applications owing to their high luminescence properties, hardness, and high-optical transparency together with mechanical and chemical stability.[4] Gallium garnets have larger unit cell volumes, higher density, higher refractive index and compositional disorder driven by the high solubility of the rare-earth ion in the octahedral site with higher RE^{3+} solubility than aluminium garnets.[5] Rare-earth gallium garnets can be effectively employed for energy-storage applications, thereby substituting Ga in Al-based traditional garnets. Generally, Al and Ga atoms in oxide compounds

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in supercapacitors due to its excellent conductivity and stable electrochemical performance. Hence $Nd_3Ga_xO_y$ is an ideal candidate for energy-storage devices and can pave the way for more efficient and sustainable energy solutions in the near future.

Author contributions

All the authors contributed to the study's conception and design. Materials preparation, data collection, and analysis were performed by Govarthini Seerangan Selvam, Jesman Sthevan Kovil Pitchai, Balaji Krishnasamy, Ramesh Rajendran and Thangaraju Dheivasigamani. All authors read and approved the final manuscript. Govarthini Seerangan Selvam: writing – original draft, particle synthesis, methodology. Jesman Sthevan Kovil Pitchai: electrochemical analysis, methodology. Balaji Krishnasamy: electrochemical analysis, methodology. Ramesh Rajendran: electrochemical analysis, methodology. Thangaraju Dheivasigamani: conceptualization, visualization, methodology, supervision, writing – review & editing.

Data availability

Data for this article are available at **https://drive.google.com/drive/folders/1vqXldCqUb1I5AN75DeR4f43aLJgaloU_?usp=sharing**.

Conflicts of interest

The authors declare no conflict of interest or relevant financial or non-financial interests to disclose.

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