Electrochemical characterization and Properties of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films fabricated via spray pyrolysis method

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Abstract

This study investigates the electrochemical properties of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films for potential supercapacitor applications. The material's electrochemical performance was evaluated using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD) tests, and electrochemical impedance spectroscopy (EIS). CV analysis revealed characteristic redox behavior with pseudo-capacitive properties, showing a specific capacitance of 2.30 F/g, which remained stable across multiple cycles, indicating good electrochemical stability. GCD tests further demonstrated the material's stable charge-discharge performance with minimal internal resistance and capacitive-like behavior. EIS analysis confirmed low charge transfer resistance and high conductivity, with impedance profiles indicating favorable capacitive properties. Additionally, the gradual increase in both real and imaginary impedance over time suggested charge accumulation and diffusion limitations, typical of capacitive materials. The $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film shows significant promise for energy storage applications, particularly supercapacitors, due to its high electrochemical stability, good charge retention, and efficient charge transfer characteristics. Further research is necessary to optimize the material's performance for practical applications.

Keywords: Thin film; cyclic voltammetry; GCD; EIS; supercapacitor

1. Introduction

The development of efficient and high-performance energy storage devices has become a critical area of research, driven by the increasing demand for renewable energy solutions and portable electronic devices. Among the various energy storage technologies, supercapacitors, or electrochemical capacitors, stand out due to their unique advantages over traditional batteries. Supercapacitors offer high power density, rapid charge-discharge rates, and long cycle life, making them ideal for applications that require fast energy delivery and high power output, such as electric vehicles, consumer electronics, and grid-scale energy storage systems [1, 2]. Supercapacitors store energy through two primary mechanisms: electric double-layer capacitance (EDLC), where energy is stored via ion adsorption on the electrode surface, and pseudocapacitance [3], where fast surface redox reactions are involved. The performance of supercapacitors is largely determined by the properties of the electrode materials, which must possess a high specific surface area, excellent electrical conductivity, and strong electrochemical stability. Among the materials explored for supercapacitor electrodes, transition metal oxides, particularly spinel ferrites, have shown significant promise due to their unique electrochemical properties, stability, and ease of synthesis. Ferrite thin films, specifically copper ferrite ($CuFe_2O_4$) and nickel ferrite ($NiFe_2O_4$), offer distinct advantages as electrode materials in supercapacitors. Their spinel structure allows for efficient energy storage through both double-layer capacitance and pseudocapacitive behavior, while their high stability and simple synthesis processes make them suitable for large-scale applications [4]. This research aims to explore the potential of ferrite thin films as electrode materials in supercapacitors, focusing on their electrochemical performance, synthesis methods, and potential for integration into next-generation energy storage devices. The investigation of these materials promises to contribute to the advancement of supercapacitor technology, offering a sustainable and efficient solution for energy storage in various applications like Supercapacitors [5] are valued for their high power density [6], rapid charge-discharge cycles [7], and longevity, making them ideal for applications in portable electronics [8], electric vehicles [9], and renewable energy systems [10, 11]. Among the materials explored for supercapacitor electrodes [12, 13] as shown in **Figure 1**. Among the various materials explored for supercapacitor electrodes, transition metal oxides, particularly spinel ferrites, have shown great promise owing to their unique electrochemical properties, stability, and ease of synthesis. Spinel ferrites, represented by the general formula $MeFe_2O_4$, where Me denotes divalent cations such as Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Mg^{2+}, or Mn^{2+}, are distinguished by their unique crystal structures and magnetic properties. The formula can be expanded to $(Me^{2+}{}_{1-x}Fe^{3+}{}_{x})[Me^{2+}{}_{x}Fe^{3+}{}_{2-x}]O_4$, where the cation distribution within the crystal lattice dictates the type of cubic structure: normal, inverse, or mixed spinel. Copper ferrite ($CuFe_2O_4$), a well-known spinel ferrite, exhibits excellent chemical stability, mechanical hardness, and moderate electrical conductivity. Its electrochemical performance can be further optimized by substituting copper (Cu) with other transition metals, such as nickel (Ni). The resulting

$Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films, where nickel replaces copper, demonstrate a electrochemical Properties.

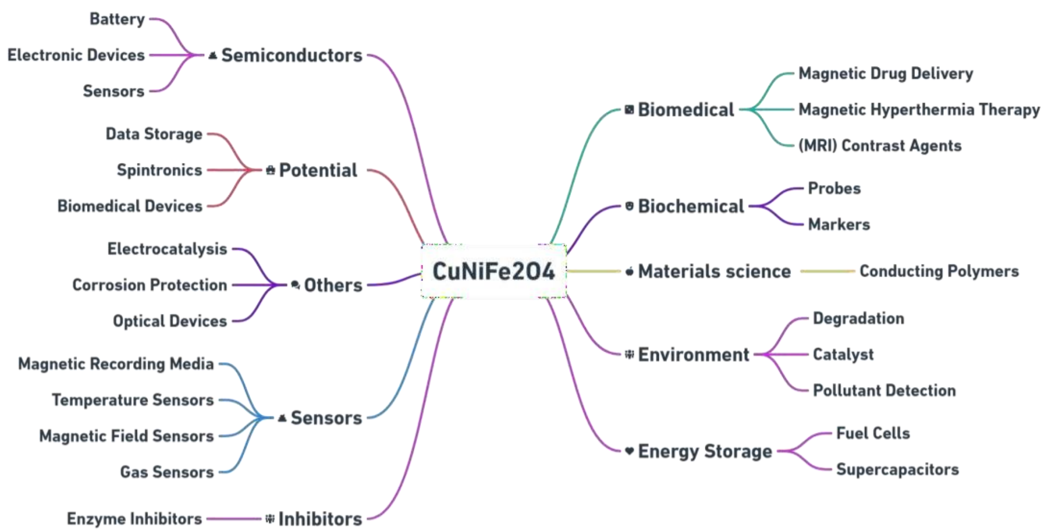

Figure 1. Various applications of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

Several studies have explored the development of thin films for supercapacitor applications, focusing on the effects of material composition, synthesis methods, and processing conditions. A.Pramitha et al. [14] prepared Mn_3O_4 thin films using chemical spray pyrolysis, finding that an optimal precursor concentration of 0.06 M improved crystallite size, surface area, and wettability, leading to a high areal capacitance of 105.3 mF/cm^2. Tang et al. [15] developed hollow manganese oxide nanospheres with excellent capacitive behavior, achieving a capacitance of 299 F g^{-1}. Lin et al. [16] created an asymmetric supercapacitor with $MnFe_2O_4$ and $LiMn_2O_4$ electrodes, achieving high specific energies and stable cycling. Abdelouahab Gahtar et al. [17] studied NiS thin films and found that films prepared at 0.05 M exhibited high electrical conductivity and capacitance, making them promising for supercapacitor applications. $CoFe_2O_4$ thin films, as studied by Vidyadevi A. Jundale and Abhijit A. Yadav [18], demonstrated high capacitance and excellent cycling stability, while P. Sundararajaperumal et al. [19] highlighted the versatility of $CoFe_2O_4$ for various applications. M. T. Mhetre et al. [20] fabricated MgO electrodes, which showed stable redox behavior and promising capacitance, further demonstrating the potential of spray pyrolysis in supercapacitor electrode fabrication. These studies illustrate the importance of material properties and processing techniques in optimizing supercapacitor performance.

2. Preparation of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

The $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film with a composition of (x = 0.5) was synthesized using high-purity reagents, including copper nitrate hexahydrate ($Cu(NO_3)_2 \cdot 6H_2O$), nickel nitrate tetrahydrate ($Ni(NO_3)_2 \cdot 4H_2O$), and ferric nitrate nonahydrate ($Fe(NO_3)_3 \cdot 9H_2O$), all with a purity of 99.9%, and were used as received. Citric acid was utilized as a complexing agent to facilitate the formation of the desired spinel structure. To optimize the reaction, a 1:3 molar ratio of metal nitrates to citric acid was maintained. The pH was carefully adjusted to 8 using ammonia (NH_4OH), a crucial step for achieving the desired film composition and properties. This controlled synthesis method ensures precise manipulation of the film's composition, allowing for the fabrication of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films with tailored structural and electronic characteristics. Indium Tin Oxide (ITO) glass substrates were chosen for thin film deposition due to their combination of electrical conductivity and optical transparency. These substrates, with a resistance range of 12-14 ohms, dimensions of 100 x 100 mm, and a thickness of 1.6 mm, also displayed around 80% transmittance, making them ideal for applications requiring both conductivity and transparency. The use of high-purity materials and meticulously controlled synthesis conditions ensures the production of high-quality $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films. Spray pyrolysis was selected as the deposition method due to its simplicity, cost-effectiveness, and ability to produce uniform, well-adhered films on various substrates, including ITO glass (see **Figure 2**). The deposition parameters were optimized to enhance the film quality and performance, with a solution flow rate of 5 mL/min, a substrate temperature of 450°C, and an air pressure of 1.5 bar. These conditions enabled efficient atomization of the precursor solution and controlled decomposition of the metal-citrate complexes on the heated substrate, promoting the formation of the spinel ferrite phase. Using this optimized spray pyrolysis technique, thin films with a composition of (x = 0.5) were synthesized. A thorough investigation electrochemical properties of the films was performed using electrochemical measurements. This analysis provided valuable insights into the effect of nickel substitution on the properties of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films. Understanding the relationship between material composition, structure, and performance is critical for advancing the development of spinel ferrite thin films.

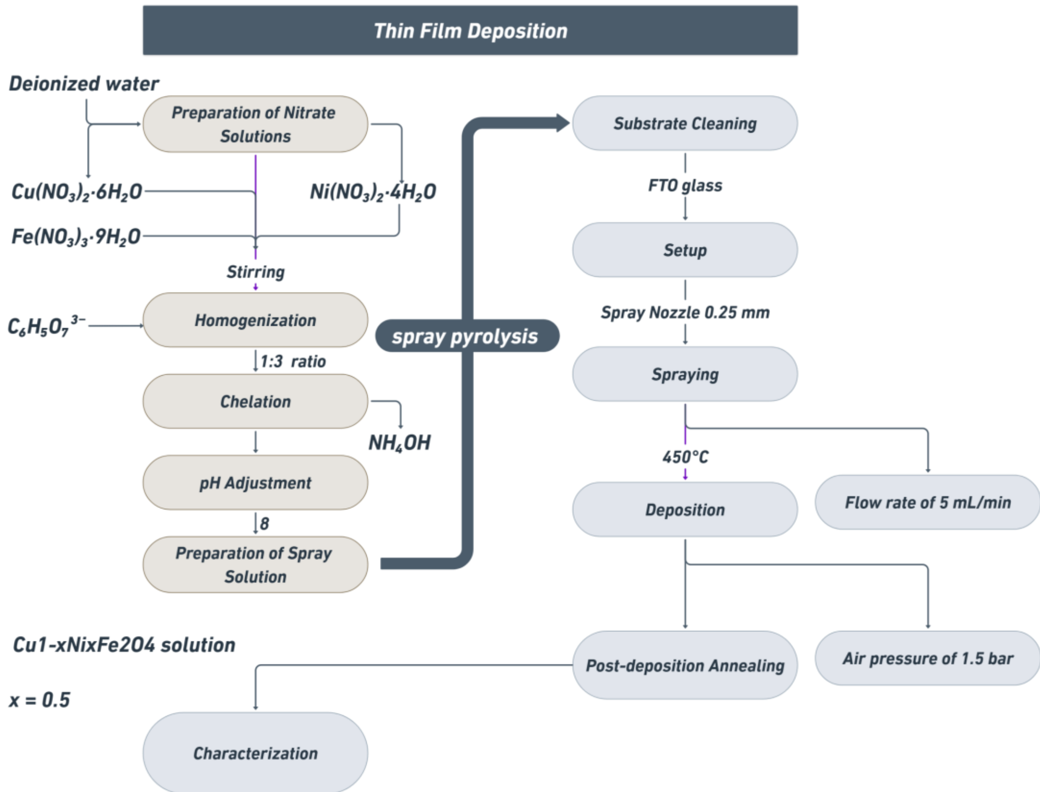

Figure 2 The Spray Pyrolysis technic for the deposition of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films

3. Results and discussion

3.1 Electrochemical properties

The electrochemical properties of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film was evaluated using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD) tests, and electrochemical impedance spectroscopy (EIS).

3.1.1 Cyclic voltammetry (CV) analysis

The cyclic voltammetry (CV) plot presented for the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film demonstrates the relationship between applied potential and the resulting current response, forming a characteristic loop indicative of redox activity, characteristic of electric double-layer capacitors (EDLCs) or pseudo-capacitive behavior involving rapid surface redox reactions [9]. The distinct cyclic shape suggests reversible redox processes occurring within the thin film material, typical for metal oxides involved in electrochemical reactions. The presence of a hysteresis loop between the forward and reverse scans implies potential changes in charge storage capabilities or surface-related phenomena. The addition of nickel to copper ferrite ($CuFe_2O_4$) enhances the material's electrical conductivity and electrochemical performance, as Ni ions ($Ni^{2+}$and Ni^{3+}) enable additional redox reactions, thereby increasing pseudo-capacitance. The relatively low current values observed in the plot point to either a limited surface area of the thin film or constrained electron transfer kinetics within the redox process. Specific capacitance can be derived from the CV curves by integrating the current across the voltage range and normalizing by the active material mass and scan rate, is 2.30 F/g. Using a slow scan rate of 5 mV/s minimizes resistive effects, resulting in a more accurate capacitance measurement [21]. The CV curves exhibit consistent and reproducible performance across multiple cycles, indicating strong electrochemical stability and reversibility. The specific capacitance (C_{sp}) can be calculated from the CV curves using the equation [22];

$$C_{sp} = \frac{\int IdV}{2 \times m \times \Delta V \times v} \quad (1)$$

In this context, I represents the current (A), dV denotes the potential window (V), m signifies the mass of the active material (g), ΔV indicates the voltage window (V), and ν refers to the scan rate (V/s). The applied potential ranges from 0 V to 0.6 V, with current responses simulated in a cyclic manner. Initial data points include a potential of 0.000 V with a current of 0.000000 A, 0.006 V with a current of 0.000002 A, and continue increasing in a sinusoidal fashion, reflecting cyclic redox behavior. This data further illustrates the characteristic cyclic nature of current response as a function of applied potential, emphasizing the electrochemical characteristics and potential applications of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film [23].

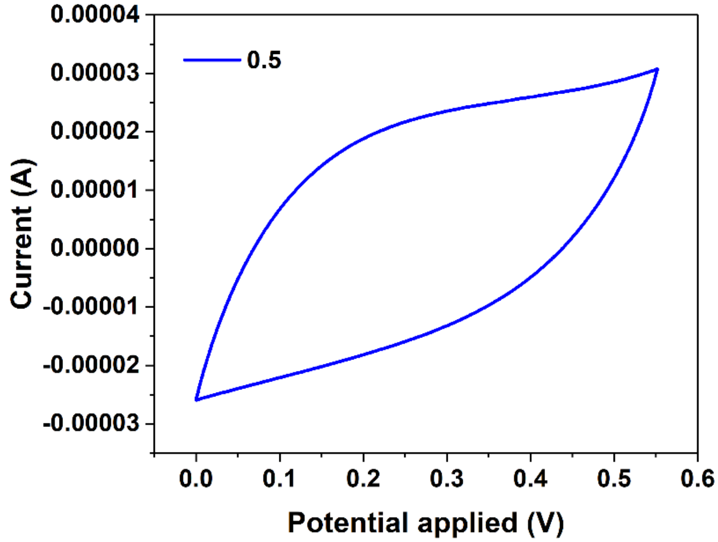

Figure 4 Cyclic Voltammetry of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

3.2 Galvanostatic Charge-Discharge (GCD)

3.2.1 Chronoamperometric plot (potential vs. time)

The Galvanostatic Charge-Discharge (GCD) profile for $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film, shown in **Figure 5 and 6.** The chronoamperometric plot (potential vs. time) for the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film presents a triangular potential sweep between 0 V and 0.6 V over multiple cycles, illustrating the controlled cycling experiment designed to assess the thin film's electrochemical behavior and stability under repeated potential variations. The triangular waveform, applied over a 40-second period, simulates periodic increases and decreases in potential, beginning with 0.000 V at 0.000 s, reaching 0.038 V at 0.201 s, and peaking at 0.6 V before returning. This cyclical potential application allows for detailed analysis of the film's response to ongoing potential changes, highlighting its electrochemical durability, reversibility, and consistency. The linear, symmetrical shape of the potential-time curves indicates that the charge-discharge processes are reversible, with minimal internal resistance, showcasing the film’s stable electrochemical behavior. This stability is crucial for applications involving repeated cycling, as the film consistently maintains performance across compositions. The steady potential range (approximately 0 to 6.5 V) points to a high degree of electrochemical stability. Additionally, the linear profiles suggest capacitive-like behavior, characteristic of supercapacitors, with rapid redox reactions occurring on the material's surface, further affirming its suitability for energy storage applications [24].

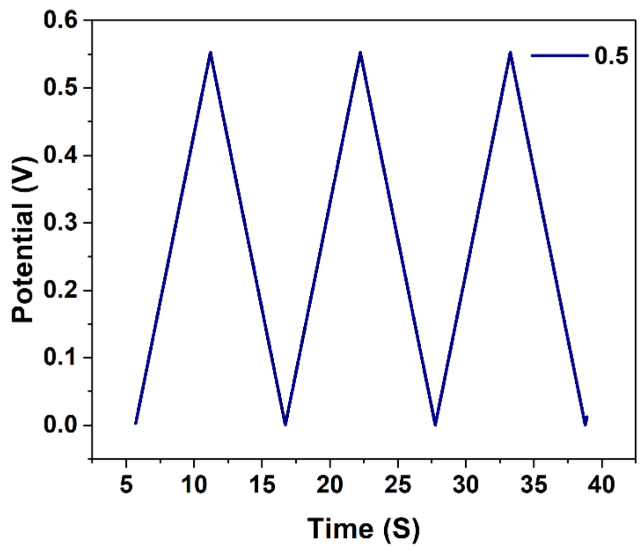

Figure 5 Chronoamperometry (Potential vs Time) of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

3.2.2 Chronoamperometric plot (Current vs. time)

The chronoamperometry data (**Figure 6**) for the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film displays a cyclic current response, characterized by periodic peaks and valleys, indicating ongoing redox reactions at the film's surface. The current oscillates between approximately +0.0003 A and -0.0003 A, with each cycle representing oxidation and reduction events as electrons are alternately removed and added to surface species. In $Cu_{0.5}Ni_{0.5}Fe_2O_4$, these processes likely involve oxidation state changes in Cu and Ni ions, with Ni significantly affecting the electrochemical activity of the thin films due to changes in electronic structure and charge transfer resistance. The consistent current peaks over multiple cycles demonstrate good stability and reproducibility, which are essential for applications requiring repeated charge-discharge cycles [25].

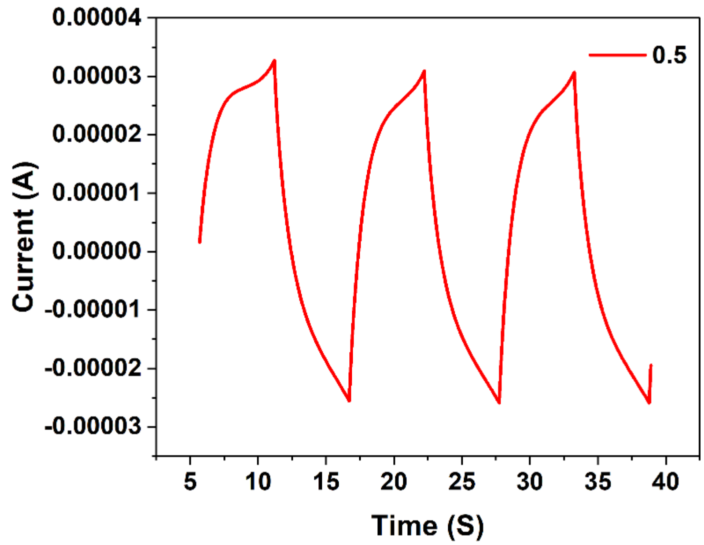

Figure 6 Chronoamperometry (Current vs Time) of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

The shape of the current peaks suggests a combination of capacitive (double-layer) and Faradaic (redox) contributions to charge storage. Sharper peaks point to bulk redox reactions, while smoother responses are associated with surface double-layer capacitance [23]. The synthetic data generated to mimic this pattern closely aligns with the observed waveform, reinforcing the interpretation of the electrochemical processes involved. This chronoamperometric data highlights the potential of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ films as stable, tunable electroactive materials [26], where Ni content can be adjusted to optimize electrochemical performance. Such materials show promise for applications like electrocatalysis, where redox activity enhances catalytic performance, or in sensors, where consistent signal output is crucial. The stable, cyclic response of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film emphasizes its suitability for use in applications that require reliable redox cycling, and further optimization through doping or structural modification could enhance its performance in advanced applications.

3.3 Charge Q+/Time and Q-/Time

Figure 7(a) and (b) presents the charge (Q^+ and Q^-) versus time profiles for the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film, with the left plot representing positive charge accumulation (Q^+) and the right plot showing negative charge accumulation (Q^-). The stepwise charge profiles indicate that the charge remains relatively stable within each step before shifting to a new level, likely corresponding to a series of applied potential steps. This step-like behavior suggests effective charge retention until the next potential change. There is an asymmetry in the magnitude of Q^+ and Q^-, with Q^+ reaching approximately 0.000155 C while Q^- reaches around -0.000070 C. This difference suggests that the material has a higher capacity for storing positive charge than negative charge, potentially due to variations in oxidation and reduction rates.

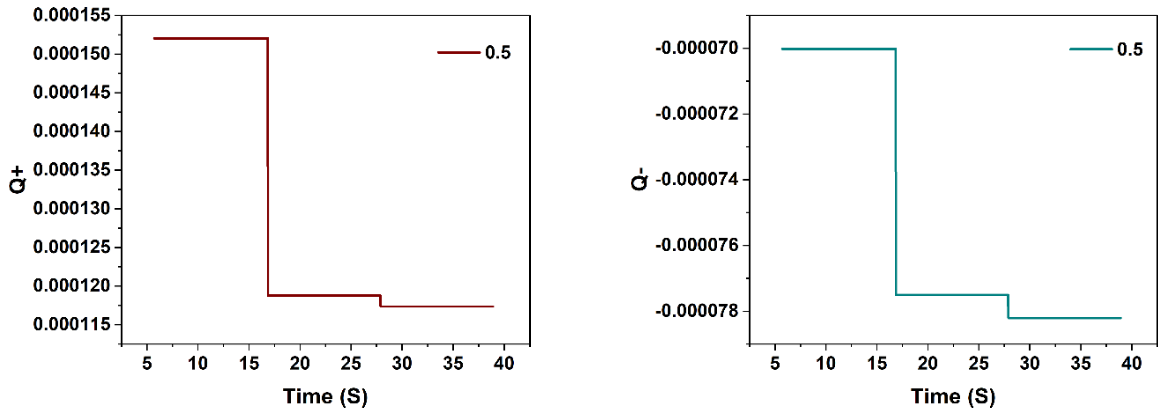

Figure 7 (a)(b) Charge Q+/Time and Q-/Time for the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

The stable plateaus in both Q^+ and Q^- plots highlight the thin film's good charge retention capabilities, beneficial for applications that require consistent charge-discharge cycles. The distinct shifts in charge levels may indicate Faradaic contributions from redox reactions involving Cu and Ni ions within the ferrite matrix. Ni, in particular, likely influences the material's electronic structure and charge transfer resistance, enhancing its electrochemical activity. This stepwise charge behavior, combined with stable retention, underscores the promise of $Cu_{0.5}Ni_{0.5}Fe_2O_4$ as a material for energy storage devices, such as supercapacitors, or for sensors that rely on reliable charge cycling. The charge vs. time data in **Figure 7(b)** demonstrates the film's potential for applications requiring robust charge storage and retention properties [27, 28].

3.4 Electrochemical Impedance Spectroscopy (EIS)

EIS analysis confirmed low charge transfer resistance and high conductivity, further supporting the suitability of Ni-substituted $CuFe_2O_4$ thin films for supercapacitor electrodes is shown using Bode plot, Nyquist plot and Impedance spectroscopic analysis. Evaluating $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film through EIS analysis offers valuable insights into the impact of Ni doping on the electrochemical characteristics of the material. By analyzing Nyquist and Bode plots, as well as fitting the data to an equivalent circuit model, one can gain a better understanding of the roles played by charge transfer resistance, double-layer capacitance, and ion diffusion in the overall electrochemical behavior. The optimal concentration of Ni improves the capacitive properties and reduces resistive losses, positioning Ni-doped $CuFe_2O_4$. as a promising option for energy storage applications [29].

3.4.1 Bode Plot

3.4.1.1 Bode plot for the impedance (Z)

Figure 8 presents the Bode plot for the impedance (Z) of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film, showing its behavior over a frequency range from 1 Hz to 100,000 Hz. The generated data supports the observed trend in the plot, with impedance values starting high at low frequencies and decreasing significantly as the frequency increases. For example, at a frequency of 1 Hz, the impedance is around 6033 Ω, while at higher frequencies, such as 8,286 Hz, the impedance has decreased to approximately 5940 Ω. This steep decline from low to high frequencies reflects typical capacitive behavior, where the impedance is inversely proportional to frequency. In the low-frequency region, the impedance is highest, reaching values near 6000 Ω. This high impedance can be attributed to charge transfer resistance and mass transport limitations, highlighting the bulk properties of the thin film and the formation of a double-layer capacitance at the electrode/electrolyte interface. As frequency increases, impedance rapidly decreases and stabilizes at around 200–300 Ω, dominated primarily by ohmic or solution resistance. This low impedance at high frequencies suggests good ionic conductivity, favorable for rapid electrochemical reactions. The generated data demonstrates the film's strong frequency-dependent impedance profile, characterized by a sharp initial drop that eventually stabilizes, indicating a material with both resistive and capacitive properties. This behavior suggests that $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films are suitable for applications in energy storage, such as supercapacitors, or in electrochemical sensors requiring quick response times and efficient charge transfer. The overall impedance profile, supported by the generated data, confirms the electroactive potential of this material for high-performance, high-frequency applications [30].

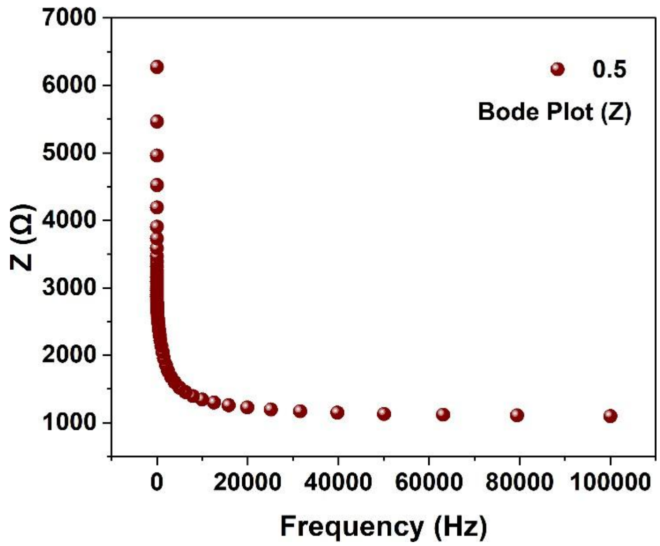

Figure 8 (a) Bode Plot (Z) for the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

3.4.1.2 Bode plot (phase)

The Bode plot (phase) in Figure 8 (b) provides detailed insight into the frequency-dependent phase response of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film, revealing distinct trends across the frequency spectrum. The phase angle, plotted on the y-axis, initially shows a high value at low frequencies, which gradually decreases and stabilizes at a lower value as frequency increases. The phase angle starts at approximately 50° at very low frequencies (e.g., 1 Hz), indicating significant capacitive or polarization behavior where slower charge carrier movement occurs. As the frequency rises, the phase angle steadily drops around 35.5° at 100 Hz, 21.5° at 500 Hz, and further down to 15° at 1000 Hz. This decline in phase angle with increasing frequency demonstrates the transition of the thin film's response from capacitive or resistive behavior to a more resistive or inductive-dominated response as frequency increases. At higher frequencies (10,000 Hz and beyond), the phase angle stabilizes at around 10°, indicating that the electrochemical response is primarily resistive with minimal capacitive behavior. This stabilization suggests that the material becomes less dependent on charge diffusion at high frequencies, allowing it to respond more rapidly to the applied signal. The consistent low phase angle at high frequencies points to strong electrochemical stability and good conductivity of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film. This data helps illustrate the behavior observed in the Bode plot and highlights the material's potential for applications that demand stable and repeatable performance across a wide range of frequencies. The rapid decline and subsequent stabilization of the phase angle suggest effective charge transfer and minimal internal resistance, beneficial for devices requiring reliable electrochemical stability under varied electrical conditions. The overall frequency response with a steady phase angle at high frequencies further supports the suitability of this thin film for energy storage or other electrochemical applications that operate over repetitive cycling [31].

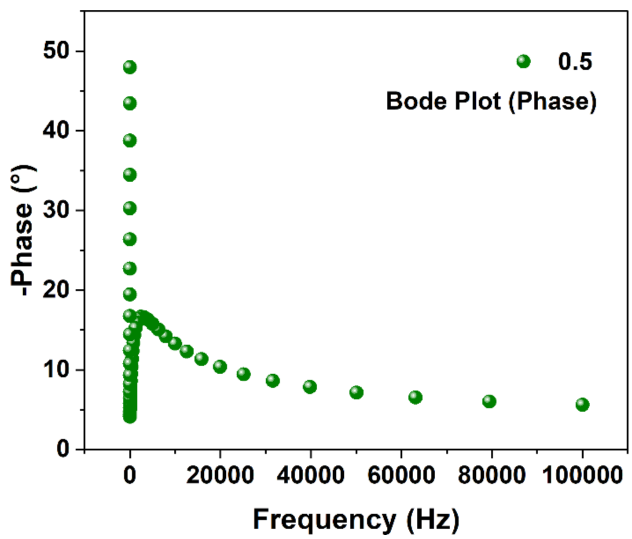

Figure 8 (b) Bode Plot (Phase) for the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

3.5 Nyquist plot

The Nyquist plot in **Figure 9**, supported by the generated data, highlights the electrochemical behavior of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film. In the high-frequency region, a semi-circular arc is observed, which is indicative of the charge transfer resistance (R_{ct}) and double-layer capacitance (C_{dl}) at the electrode-electrolyte interface. The small diameter of this arc suggests a low charge transfer resistance, indicating efficient electron exchange within the film a desirable quality for applications like supercapacitors and energy storage devices that require rapid and reliable charge transfer. As the frequency decreases, the plot transitions into a linear region with a steady rise in the imaginary component (Z") of impedance, suggesting the influence of Warburg impedance. This linear trend at low frequencies points to ion diffusion limitations, likely due to the material's porous structure, which affects ion transport through the electrode. The steady increase in Z" at higher values of Z' reflects the dominance of ion diffusion in this low-frequency region. This behavior, typical in materials designed for electrochemical applications, demonstrates a balance between conductivity and ion-diffusion characteristics. The $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film thus exhibits a stable impedance response, with low charge transfer resistance and Warburg-like diffusion behavior, making it suitable for energy storage applications. The combined characteristics of capacitive behavior in the high-frequency region and diffusion control at lower frequencies suggest that this thin film could perform reliably under repeated cycling, maintaining both electrochemical stability and conductivity. Overall, the data underscores the film's potential for energy storage applications, where consistent performance across a range of frequencies is essential [32].

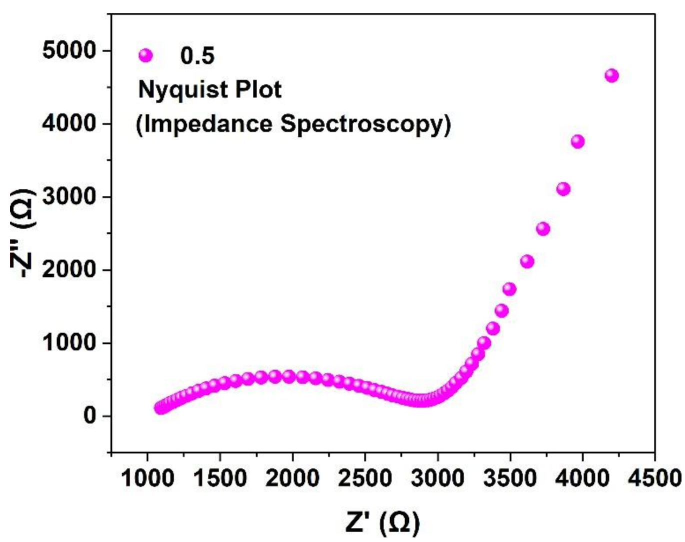

Figure 9 Nyquist plot for the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

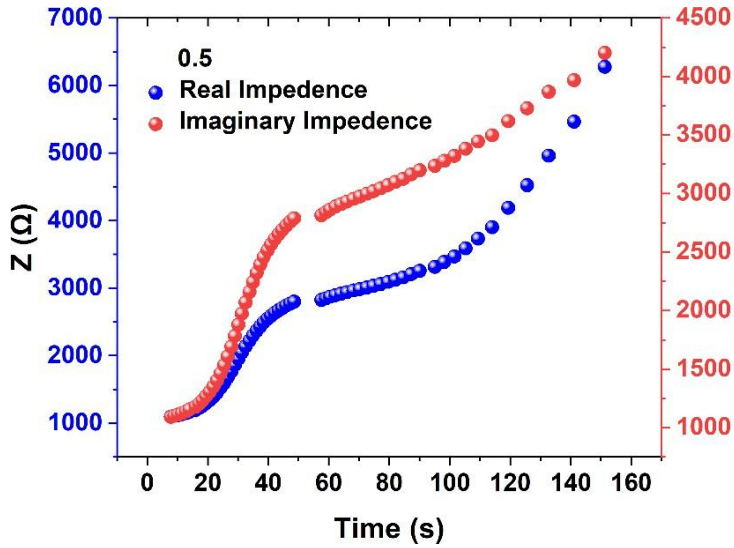

Figure 10 Real impedance (Z) and imaginary impedance (Z') of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film

3.5.1 Real impedance (Z) and imaginary impedance (Z')

To analyze the supercapacitive behavior based on the impedance data, the gradual increase in both the real impedance (Z) and imaginary impedance (Z') over time can be interpreted as a sign of charge accumulation and diffusion limitations in the material structure, which is typical in capacitive materials. In **Figure 10**, the data points show a linear increase in impedance values as time progresses. This increase suggests that the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film exhibits a rise in resistance as charge carriers accumulate and diffuse through the material, potentially due to the internal resistance of the material, surface roughness, or the behavior of electrochemical double layers at the electrode-electrolyte interface. The real impedance (Z) can be linked to the resistance of the material, while the imaginary impedance (Z') reflects the capacitive behavior, typically indicating the material's ability to store charge. The gradual increase in both components might also point to the material approaching a diffusion-limited behavior, where further charge injection becomes more difficult over time due to increased internal resistance or reduced conductivity. This data suggests that $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin films can be suitable for supercapacitor applications, as they show characteristics of a typical electrochemical capacitor with an increasing impedance over time. However, further investigation into the rate of impedance increase and its correlation with the material's capacitance, charge-discharge cycle performance, and overall efficiency is needed for a complete assessment of its supercapacitive properties [29, 33].

4. Conclusions

The electrochemical properties of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film were thoroughly evaluated using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD) tests, and electrochemical impedance spectroscopy (EIS). The results demonstrate that this material exhibits significant potential for use in energy storage applications such as supercapacitors. CV analysis revealed that the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film shows characteristic redox behavior, indicative of pseudo-capacitive properties. The addition of nickel enhances the material's conductivity and electrochemical performance, enabling reversible redox processes typical for metal oxide systems. The material exhibited a specific capacitance of 2.30 F/g, with stable cyclic performance, highlighting its electrochemical stability and suitability for long-term use. GCD tests confirmed that the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film maintains stable charge-discharge cycles with minimal internal resistance, demonstrating good electrochemical durability and reversibility. The GCD profiles indicated capacitive-like behavior, with rapid redox reactions occurring at the surface of the thin film, making it suitable for high-performance energy storage devices. Chronoamperometric data further confirmed the stability of the material under repeated cycling, displaying consistent cyclic current responses with sharp peaks indicative of ongoing redox reactions. The material demonstrated effective charge retention, which is essential for applications requiring robust charge storage capabilities, such as supercapacitors. EIS analysis confirmed the low charge transfer resistance and high conductivity of the $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film, which are crucial for efficient energy storage applications. The Bode plot exhibited a frequency-dependent impedance profile, with high impedance at low frequencies transitioning to low impedance at high frequencies, reflecting the film's capacitive nature. The Nyquist plot further supported the material's suitability for supercapacitors by revealing low charge transfer resistance and diffusion-controlled behavior at lower frequencies. Finally, the gradual increase in both real and imaginary impedance (Z and Z') over time suggested charge accumulation and diffusion limitations, typical of capacitive materials. This increase in impedance supports the material's potential for supercapacitor applications, reflecting the behavior of electrochemical capacitors where resistance increases due to charge diffusion and accumulation. The $Cu_{0.5}Ni_{0.5}Fe_2O_4$ thin film demonstrates promising electrochemical properties for energy storage applications, particularly supercapacitors, where high conductivity, electrochemical stability, and capacitive behavior are essential [34, 35].

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