## Influence of Gas Diffusion Layer Current Collector on Electrochemical Performance of Ni(OH)₂ Nanostructures

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Influence of Gas Diffusion Layer Current Collector on Electrochemical Performance of Ni(OH)$_2$ Nanostructures

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ABSTRACT

In this work, we report the electrochemical performance of Ni(OH)$_2$ on gas diffusion layer (GDL) substrate owning to the fact that different current collectors resulting in different electrochemical performances. The Ni(OH)$_2$ working electrode was successfully prepared by a simple method and its electrochemical performance was investigated in 1M NaOH electrolyte. The electrochemical results show that Ni(OH)$_2$ on GDL substrate provides the maximum specific capacitance value of 418.11 F·g$^{-1}$ at 1 A·g$^{-1}$. Furthermore, the Ni(OH)$_2$ electrode delivers a high specific energy of 17.25 Wh·kg$^{-1}$ at specific power of 272.5 W·kg$^{-1}$ and the cyclic stability retains about 81% after 1000 cycles. Clearly, SEM coupled with EDS results imply that sodium deposition occurring after long-time cycling causes the reduction of the specific capacitance. The present work suggests that light-weight of GDL could be considered as a promising current collector in electrochemical studies of Ni-based electroactive materials for energy storage applications in order to overcome the problem of oxide layer on metal-foam substrates.

Keywords: Hydrothermal synthesis; Nickel hydroxide; Gas diffusion layer; Sodium deposition; Electrochemical capacitor
1. Introduction

Electrochemical capacitors are one of the energy storage devices which generally consists of the following four main parts of current collector, separator, active material, and electrolyte [1]. One of these parts which determines the electrochemical performance is current collector. Current collector, known as substrate, plays an significant roles in electrochemical capacitors including [2]: (i) collecting and conducting electricity from the electrode to power source and (ii) supporting the active materials or serving as a holder of the active materials. Hence, the performance of electrochemical capacitor depends on both physical and chemical properties of current collector [3-4]. Ni foam is a widely used current collector in laboratory research due to its cheap, mechanical strength, inertness, and relatively low toxicity [5]. Generally, opened-pore Ni-foam is produced by coating Ni metal on a polymer type matrix of polyurethane using chemical vapor deposition (CVD) or electrochemical deposition technique. Therefore, the oxide layer can easily form on surface of Ni foam by exposing it in air [6]. It was reported that this layer provided an overpotential that reduced the power output [5]. Also, an errors in specific capacitance value because of the presence of nickel oxide/hydroxide on the surface of Ni foam were reported [7]. To overcome this problem, high surface area of carbon fiber paper was used as current collector. Gas diffusion layer (GDL) is one of a carbon-based current collectors which is generally used in several applications such as fuel cell [8-11] and Li-ions batteries [12]. Generally, GDLs are composed of either woven or non-woven carbon fiber arrangement with interconnected porous structure [13]. The properties of GDLs such as low sheet resistance, large surface area, and light-weight have attracted much attention as current collector for electrochemical capacitor application [14]. For active materials, nanosized of Ni(OH)₂ was considered as a very promising electroactive materials due to its high capacitance value, low cost, and easy processing [15-16].
In this work, we offer a simple method for the working electrode preparation, in which a light-weight carbon fiber of GDL was used as current collector for electrochemical studies of Ni(OH)$_2$. The electrochemical studies of Ni(OH)$_2$ on GDL substrate was investigated via three-electrode system in 1M NaOH aqueous electrolyte. The prepared Ni(OH)$_2$ electrode reached the maximum specific capacitance value of 418.11 F·g$^{-1}$ at current density of 1 A·g$^{-1}$ and the capacitance retained 81% after 1000 cycles. The reduction of the specific capacitance value after 1000 cycles is also proposed and discussed in this work.

2. Experimental

2.1 Synthesis of Ni(OH)$_2$ nanostructures

All the chemicals were of analytical grade and were used without further purification. In this work, nanostructures of Ni(OH)$_2$ were synthesized by a hydrothermal method as previously reported [17]. Briefly, the NaOH solution was dropped into the nickel chloride solution and it was washed with DI water. After that, the NaOH solution was directly added into the resulting precipitate and it was then transferred to a Teflon-lined stainless-steel autoclave. The autoclave was heated up and maintained at 160ºC for 20 h. The obtained green precipitate of Ni(OH)$_2$ was finally washed with DI water and subsequently dried in vacuum oven at 70ºC.

2.2 Preparation of working electrode

In the preparation of working electrode, an active material of Ni(OH)$_2$, conducting agent of carbon black, and binder of polyvinylidene difluoride in a given mass ratio of 80:10:10 were hand-mixed using aggregate mortar and pestle. N-methyl pyrrolidone (NMP) solution of 200 µL was added into the mixed powder. To obtain a homogeneous slurry, the mixture was then shaken for 6 h by using a mini-shaker. The obtained slurry of 1 µL was dropped onto both sides of GDL substrate (MGL 190, AvCarb material solutions company), which was placed on the hotplate at temperature of ~90ºC, within the active area of 1x1 cm$^2$ as shown in Fig. 1. Finally,
the dried working electrode was naturally cooled down to room temperature and the electrochemical performance was further investigated.

**Fig. 1.** Schematic representation for the electrode preparation of Ni(OH)$_2$ on GDL substrate.

### 2.3 Material characterization and electrochemical measurement

The crystal structure of bare GDL substrate, powder Ni(OH)$_2$, and the prepared working electrode was characterized by X-ray diffraction (XRD) technique on Bruker D2 using Cu K$\alpha$ radiation ($\lambda = 1.5406$ Å) at step time of 0.5 s and scanning rate of 0.02° min$^{-1}$ in the 2$\theta$ range from 10 to 80°. The surface morphologies and their corresponding EDS spectra were revealed by FE-SEM images. The electrochemical performances of Ni(OH)$_2$ on GDL substrate were performed in 1M NaOH electrolyte using three-electrode system. A platinum plate was used
as reference electrode and Ag/AgCl saturated in 3M KCl solution was used as counter electrode. The electrochemical performances were evaluated using Metrohm Autolab PGSTAT 302N potentiostat/galvanostat instrument via three techniques, consisting of cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS). Before the electrochemical measurement could be started, the working electrode was soaked in 1M NaOH for 12 h. The specific capacitance \( C \), energy density \( E \), and power density \( P \) of Ni(OH)\(_2\) on GDL substrate were calculated by using the following equations [18]:

\[
C = \frac{I\Delta t}{m\Delta V}\quad (1)
\]

\[
E = \frac{1}{2}C\Delta V^2\quad (2)
\]

\[
P = \frac{E}{\Delta t}\quad (3)
\]

where \( C \) is specific capacitance (F·g\(^{-1}\)) obtained from GCD technique, \( I \) is the discharge current (A), \( m \) is the mass of active material (g), \( \Delta t \) is the discharge time (s), \( \Delta V \) is the operating voltage (V), \( E \) is the energy density (Wh·kg\(^{-1}\)), and \( P \) is the power density (W·kg\(^{-1}\)).

3. Results and discussion

3.1 Characterization of the working electrode

The XRD patterns of bare GDL substrate, Ni(OH)\(_2\) powder, and the prepared working electrode are presented in Fig. 2. As seen in Fig. 2, XRD pattern of the prepared working electrode shows a series of sharp peaks within a 2\( \theta \) ranging from 10-80\(^{\circ}\). The diffracted peaks at 2\( \theta \) ~ 19.3, 33.0, 38.5, 52.2, 59.0, 62.6, 69.3, 70.5, and 72.7\(^{\circ}\) correspond to (001), (100), (101), (102), (110), (111), (200), (103), and (201) planes of \( \beta \)-Ni(OH)\(_2\) with hexagonal crystal structure (JCPDS file no. 14-0117), respectively. The standard diffraction peaks are indicated by blue lines. On the other hands, two diffraction peaks at 2\( \theta \) ~ 26\(^{\circ}\) and 55\(^{\circ}\) in XRD pattern of
the prepared working electrode arise from the GDL substrate which are the characteristic peaks of (002) and (004) planes of graphite structure [19-20]. By comparing the XRD pattern of the prepared working electrode with bare GDL substrate and the synthesized Ni(OH)$_2$ powder, we can conclude that the working electrode was successfully prepared.

![XRD patterns](image)

**Fig. 2.** XRD patterns of the (a) bare GDL substrate, (b) Ni(OH)$_2$ powder, and (c) the prepared working electrode.

The surface morphologies and microstructure of bare GDL substrate and the prepared working electrode are revealed as shown in FE-SEM images of Fig. 3. It is clearly observed in those FE-SEM images that bare GDL substrate composes of a randomly arrangement of straight carbon fibers. This arrangement provides a large space between interconnected fibers which is very useful for electrochemical application in order to serve as the uninterrupted charge freeway networks for quick electron transfer [18]. After dropping the slurry on GDL substrate and dried it at ~ 90°C, the FE-SEM image in Fig. 3(b) shows that the slurry entirely covered on GDL substrate. In addition, the presence of cracks due to the solvent (NMP)
evaporation are also presented on the surface of the prepared working electrode. The high magnificent FE-SEM images of Ni(OH)$_2$ in Fig. 3(d) shows that those Ni(OH)$_2$ plates are agglomerated with providing pores on the electrode surface. These pores are beneficial for electrolyte ions in electrochemical application as their can reduce the diffusion pathway resulting in high specific capacitance value.

![Fig. 3. FE-SEM images of (a) bare GDL substrate and (b-d) the prepared working electrode with different magnifications.](image)

**3.2 Electrochemical studies**

At the beginning, two different types of bare Ni foam and GDL substrates were investigated by CV technique. Fig. 4(a) shows the comparison CV plots of bare Ni foam and GDL substrates which were measured in 1M NaOH electrolyte at scan rate of 2 mV·s$^{-1}$. As seen
in Fig. 4(a), CV curves show remarkable difference between GDL and Ni foam substrates. The CV curve of Ni foam presents redox peak in which the oxidation and reduction peaks are related to Faradaic reactions of Ni(OH)$_2$ described by the following reaction [21]:

$$\text{Ni(OH)}_2 + \text{OH}^- \leftrightarrow \text{NiOOH} + \text{H}_2\text{O} + e^-$$  \hspace{1cm} (4)

**Fig. 4.** Electrochemical characterization of Ni(OH)$_2$ electrode: (a) Comparison CV curves of Ni(OH)$_2$ on Ni foam and GDL substrates, (b) CV curves of Ni(OH)$_2$ on GDL substrate measured at different scan rates, (c) the scan rate dependent of peaks current, and (d) the contribution of capacitive and diffusion-controlled mechanism of Ni(OH)$_2$ on GDL substrate.

Therefore, the CV result in Fig. 4(a) demonstrates the existence of redox peak on Ni foam substrate without adding of any active materials. The presence of this redox peak was
reported to generate the pseudocapacitance, providing an error in the specific capacitance evaluation [7]. For this reason, GDL substrate is further used as current collector for electrochemical studies of Ni(OH)$_2$. Fig. 4(b) displays the CV plots of Ni(OH)$_2$ on GDL substrate at different scan rates within the potential window of 0.65 V. Non-rectangular CV shapes including shift of redox peaks with increasing scan rates are observed, implying that the capacitance originates from the redox reactions [22]. The shift of these redox peaks was further used for an investigation of charge storage mechanism of Ni(OH)$_2$ on GDL substrate. In general, the dependence of peak current ($i$) with scan rates ($v$) in a CV curves can be expressed according to the power law relation $i = av^b$ where $a$ and $b$ are adjustable values [23]. The plot between log ($i$) versus log ($v$) provides the slope of $b$ value. A $b$-values of 1 and 0.5 indicate that the obtained peak current is due to a capacitive and intercalation/deintercalation mechanisms, respectively [24]. As shown in Fig. 4(c), the $b$-values of oxidation and reduction process are close to 0.5, implying that charge storage mechanism of Ni(OH)$_2$ on GDL substrate arises from diffusion-controlled intercalation/deintercalation mechanism. Based on the above result, the possible charge storage mechanism of Ni(OH)$_2$ on GDL substrate measured in 1M NaOH aqueous electrolyte can be written as follows [25]:

\[
\text{Ni(OH)}_2 + \text{Na}^+ + \text{e}^- \leftrightarrow \text{NaNi(OH)}_2 \quad (5)
\]

It is well known that the combination between capacitive ($k_1v$) and diffusion-controlled intercalation/deintercalation ($k_2v^{1/2}$) mechanisms is the total charge storage in electrode following the relation given below [26-27]:

\[
i_p = k_1v + k_2v^{1/2} \quad (6)
\]

Where the slope and intercept of the plot between $i_p/v^{1/2}$ versus $v^{1/2}$ provide $k_1$ and $k_2$ values, respectively. Therefore, distinguishing the contributions arising from capacitive and diffusion-controlled intercalation/deintercalation mechanisms can be achieved. Fig. 4(d) shows the
capacitive and diffusion-controlled contributions obtained from the plot between \( i_p \sqrt{v} \) and \( v^{1/2} \) at scan rates of 1-10 mV·s\(^{-1}\). As shown in Fig. 4(d), the capacitive contribution increases with increasing scan rates, whereas the diffusion-controlled intercalation/deintercalation process decreases as scan rate increases as summarized in Table 1. As scan rate decreases, the electrolyte ions have enough time to diffuse into the electrode matrix. On the other hand, the diffusion time is limited as scan rates increase [28].

Table 1. The dependency of the capacitive and intercalation/deintercalation or diffusion-controlled mechanisms at different scan rates of Ni(OH)\(_2\) on GDL substrate

<table>
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<tr>
<th>Scan rate (mV·s(^{-1}))</th>
<th>Contribution / %</th>
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<tbody>
<tr>
<td></td>
<td>Capacitive</td>
</tr>
<tr>
<td>1</td>
<td>17.148</td>
</tr>
<tr>
<td>2</td>
<td>22.645</td>
</tr>
<tr>
<td>3</td>
<td>26.389</td>
</tr>
<tr>
<td>4</td>
<td>29.276</td>
</tr>
<tr>
<td>5</td>
<td>31.639</td>
</tr>
<tr>
<td>10</td>
<td>39.561</td>
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Fig. 5(a) shows GCD plots of Ni(OH)\(_2\) on GDL substrate at a current density of 1-10 A·g\(^{-1}\) within the potential window of 0.55 V. It is clearly seen in Fig. 5(a) that GCD curves compose of two different curve profiles. The linear profile indicates that the electrode store charge based on electrolyte ions sorption at the surface of electrode, while the plateau profile or battery-type behavior profile implies that the electrode store the charge based on the redox reaction or intercalation/deintercalation mechanism [29]. The specific capacitance of Ni(OH)\(_2\) on GDL substrate was calculated by using Eq. (1) and the result is presented in Fig. 5(b). At current density of 1 A·g\(^{-1}\), Ni(OH)\(_2\) on GDL substrate exhibits the highest specific capacitance value of 418.11 F·g\(^{-1}\). It is also observed that the specific capacitance values decrease with increasing...
current densities. The specific capacitance value of Ni(OH)$_2$ on different substrates was compared with other literatures and is presented in Table 2. It can be seen that the specific capacitance value of the prepared Ni(OH)$_2$ electrodes depends on substrate, electrolytes, and the applied current density and voltages. In comparison with carbon-based substrate, the prepared Ni(OH)$_2$ on GDL substrate in Table 2 provides the higher specific capacitance value than other reports.

Fig. 5. Electrochemical characterization of (a) charge and discharge curves of Ni(OH)$_2$ on GDL substrate at different current densities and (b) the calculated specific capacitance obtained from the discharge curves.

Table 2. Comparison of the specific capacitance of Ni(OH)$_2$ on different current collectors

<table>
<thead>
<tr>
<th>Sample</th>
<th>Method</th>
<th>Substrate</th>
<th>Electrolyte</th>
<th>$C_S$ / F·g$^{-1}$</th>
<th>Ref.</th>
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</thead>
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<tr>
<td>Ni(OH)$_2$ film</td>
<td>Electrodeposition</td>
<td>Titanium substrate</td>
<td>3 M KOH</td>
<td>578 F·g$^{-1}$</td>
<td>[30]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>at 0.0025 A</td>
<td></td>
<td></td>
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<tr>
<td>Ni(OH)$_2$ thin films</td>
<td>Chemical bath deposition</td>
<td>Stainless steel</td>
<td>2 M KOH</td>
<td>398 F·g$^{-1}$</td>
<td>[31]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>at 5 mV·s$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni(OH)$_2$ nanoparticles</td>
<td>Chemical precipitation</td>
<td>Ni foam</td>
<td>6 M KOH</td>
<td>255.1 F·g$^{-1}$</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>at 2 mV·s$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni(OH)$_2$ nanofibers</td>
<td>Electrodeposition</td>
<td>Carbon fiber paper</td>
<td>1 M KOH</td>
<td>277.5 F·g$^{-1}$ at 5 mV·s$^{-1}$</td>
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<tr>
<td>Planar Ni(OH)$_2$ nanoflakes</td>
<td>Chemical bath deposition</td>
<td>Carbon fibers</td>
<td>1M KOH</td>
<td>275 F·g$^{-1}$ at 1 A·g$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Ni(OH)$_2$ nanoplates</td>
<td>Hydrothermal synthesis</td>
<td>Gas diffusion layer</td>
<td>1 M NaOH</td>
<td>418.11 F·g$^{-1}$ at 1 A·g$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>This work</td>
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To gain insight into an electrochemical performance of Ni(OH)$_2$ on GDL substrate, EIS was performed in the frequency range of 0.1-100 kHz at an amplitude of 0.1 V. Fig. 6 shows the Nyquist plots of bare GDL and Ni(OH)$_2$ on GDL substrate or the prepared working electrode. Depending on frequency range, Nyquist plots are generally divided into three regions. As seen in Fig. 6, the solution resistance ($R_s$) values at the intercept of the Z'-axis in high frequency region of bare GDL substrate and the prepared working electrodes are estimated to be 1.85 and 4.28 Ω, respectively. Owning to the fact that $R_s$ value is concerned with the resistance of the substrate including layer thickness of electroactive material [35] and the $R_s$ value is explained through the following equation of $R_s = L / \sigma A$ where $L$ is the thickness of the electrode, $\sigma$ is the solution conductivity and $A$ is an area of the electrode [36]. Therefore, the higher $R_s$ value in the prepared working electrode is due to the thicker electrode after dropping the slurry on GDL substrate. In addition, the larger charge transfer resistance ($R_{ct}$) in mid-frequency region is also observed in bare GDL substrate than in the prepared working electrode. In general, $R_{ct}$ associates with electron exchanged involving the redox reaction at the electrolyte/electrode interface which is given by the following equation of $R_{ct} = RT/nF \dot{i}^0$ where $R$ is the molar gas constant, $T$ is temperature, $F$ is Faraday’s constant and $\dot{i}^0$ is exchange current density of the reaction [37]. Based on the above equation, it may be concluded that the larger $R_{ct}$ value in bare GDL substrate is due to the lack of electroactive material Ni(OH)$_2$ which limited an electron exchanged in this process. The vertical lines perpendicular to Z'-axis in low
frequency region of Fig. 6, which indicate the diffusion of the electrolyte ions in an
electrochemical reaction, are estimated to be about 82.5° and 77.4° in bare GDL and the
prepared working electrode, respectively. Therefore, this result implies the more capacitive
behavior and low ions diffusion resistance in bare GDL substrate due to an angle of the straight
line closer to 90° [38].

![Nyquist plot]

**Fig. 6.** Comparison of Nyquist plots of bare GDL and Ni(OH)$_2$ on GDL substrate measured at
the frequency range of 0.1 Hz to 100 kHz.

Long-term cyclic stability of Ni(OH)$_2$ on GDL substrate was carried out by repeating GCD
measurement at a current density of 5 A·g$^{-1}$ for 1000 cycles. As seen in Fig. 7, the capacitance
retention of Ni(OH)$_2$ on GDL substrate retains about 81% after 1000 cycles. The decay of the
capacitance value was due to the loose of electrical contact between the active material and
current collector [39]. The coulombic efficiency ($\eta$) of Ni(OH)$_2$ on GDL substrate was
calculated by using the equation of $n = t_d/t_c$ where $t_d$ is the discharging time and $t_c$ is the
charging time [40]. As a result, the coulombic efficiency is found to be about 80% after 1000
cycles.
Fig. 7. The capacitance retention and coulombic efficiency of Ni(OH)$_2$ on GDL substrate measured in 1M NaOH at current density of 5 A·g$^{-1}$ for 1000 cycles.

To further understand the long term cyclic stability of Ni(OH)$_2$ on GDL substrate, the FE-SEM images of Ni(OH)$_2$ on GDL substrate with their corresponding EDS results before and after GCD measurement for 1000 cycles are revealed. As a result, the difference in the electrode surface before (see Fig. 3(b)) and after repeating GCD measurement for 1000 cycles (Fig. 8) is observed. It can be clearly noticed in Fig. 8(a) that surface of the working electrode consists of two different colors of black and white together with the presence of cracks on the electrode surface (Fig. 8(b)) after cyclic stability measurement. The surface morphology of the prepared working electrode before the cyclic test as presented in Fig. 3(b) shows minor cracks. On the other hand, those cracks become larger after continuous repeating charge and discharge for 1000 cycles.
Fig. 8. SEM images of (a-d) surface morphologies and (e-f) the corresponding EDS spectra of Ni(OH)$_2$ on GDL substrate after repeating GCD measurements for 1000 cycles.

In general, cracks originate from the elastic mismatch between two attached surfaces and are commonly considered as defects [41]. The existence of cracks on the electrode surface was reported due to the large volume change, leading to the loss of the electrical contact between individual particles which results in capacity fading in lithium-ion battery [42].
the contrary, the excellent long-term stability was also reported by introducing cracks into NiO nanosponge due to NiO is capable expanding/contracting freely during charge/discharge process [43]. Therefore, the presence of cracks on surface of the working electrode after repeating GCD measurement for 1000 cycles suggests poor cyclic stability in this work. Interestingly, the high magnificent FE-SEM image in Fig. 8(c) shows the separation between these two colors denoted as area 1 and area 2. The magnified FE-SEM image of area 2 in Fig. 8(d) reveals the densely packed of hexagonal Ni(OH)\(_2\) plates. In contrast, the smooth surface is observed in area 1. The elemental compositions of the prepared working electrode from different detected areas are shown in Fig. 8(e-f). The EDS spectrum of the detected area 1 in Fig. 8(e) shows a small amount of nickel (Ni). Unlike the EDS spectrum of the detected area number 2 in Fig. 8(f), the amount of this element is high. Additionally, the high amount of sodium (Na) is detected in area 1 when compared with the detected area 2. This result suggests that the presence of new phase consisting of Na or Na deposition occurs after cyclic stability measurement. The schematic representation of Na deposition is proposed and shown in Fig. 9. Therefore, the decay of the specific capacitance from its initial value may be attributed due to Na deposition on surface of the working electrode as evidenced in the EDS result after long cyclic stability measurement, which is in good agreement with other literatures [44-45].

![Fig. 9. The schematic representation of Na deposition on surface of the prepared working electrode after long-term stability measurement.](image)

To get further insight into the decrease of the capacitance, ex-situ XRD characterization for the structural change of the Ni(OH)\(_2\) electrode after 1000 cycles was performed and the
result is presented in Fig. 10. In comparison with XRD pattern of the prepared Ni(OH)$_2$ electrode before cycling, the low intensity peaks of Ni(OH)$_2$ after cycling are almost disappeared and the formation of sodium peroxide (Na$_2$O$_2$) is detected. The possible reaction involving the Na$_2$O$_2$ formation is as follows [46]:

$$2\text{Na}^+ + \text{O}_2 + 2\text{e}^- \rightarrow \text{Na}_2\text{O}_2$$  \hspace{1cm} (7)

Therefore, the formation of Na$_2$O$_2$ after cycling significantly affects the cycling stability of Ni(OH)$_2$ electrode. This result is consistent with SEM coupled with EDS results as presented in Fig. 8.

![XRD patterns of the prepared Ni(OH)$_2$ electrode before and after cycling stability test.](image)

**Fig. 10.** XRD patterns of the prepared Ni(OH)$_2$ electrode before and after cycling stability test.

It is well-known that the Ragone plot is used to compare the performance of energy storage devices [47]. Fig. 11 displays the Ragone plots of Ni(OH)$_2$ on GDL substrate. It is seen in Fig. 11(a) that Ni(OH)$_2$ on GDL substrate provides the maximum specific energy of 17.25 Wh·kg$^{-1}$ at current density of 1 A·g$^{-1}$ and specific power of 2.76 kW·kg$^{-1}$ at current density of 10 A·g$^{-1}$. According to the well-known Ragone plot, the electrochemical capacitors cover a wide range of specific energy (0.05-15 Wh·kg$^{-1}$) and specific power (10-10$^6$ W·kg$^{-1}$) [48]. Therefore,
Ni(OH)$_2$ on GDL substrate as shown in Fig. 11(b) is suitable for electrochemical capacitors applications.

![Graph](image)

Fig. 11. Ragone plots of (a) Ni(OH)$_2$ on GDL substrate and (b) comparison with the well-known Ragone plot of Kötz [48].

4. Conclusion

In this work, the working electrode of Ni(OH)$_2$ was successfully prepared on GDL substrate by a simple method and its electrochemical performance was investigated in 1M NaOH electrolyte. Based on the kinetic analysis, charge storage of Ni(OH)$_2$ on GDL substrate mainly originates from diffusion-controlled intercalation/deintercalation mechanism. Within the potential window of 0.55 V, the Ni(OH)$_2$ on GDL substrate displays the highest specific capacitance of 418.11 F·g$^{-1}$ at a current density of 1 A·g$^{-1}$. The cyclic stability retains about 81% after 1000 cycles due to the presence of Na deposition on the working electrode surface as clearly indicated by SEM coupled with EDS results after repeating GCD measurement. To improve the long-term cyclic stability of Ni(OH)$_2$ on GDL substrate, the electrode preparation need to be optimized in the future work.
Acknowledgments

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