Synthesis of Li-doped Nickel Oxide Thin Film Electrodes for Electrochemical Capacitors Using Electrostatic Spray Deposition Technique

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Thin film of Li-doped nickel oxide was prepared by the electrostatic spray deposition (ESD) technique onto a Pt coated silicon wafer and Pt coated alumina substrate with different deposition temperatures. Crystal structure, surface morphology and electrochemical properties of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film were studied by means of X-ray diffraction (XRD), scanning electron microscopy (SEM) and cyclic voltammetry. It is found that the deposition temperature had a significant impact on the structure, surface morphology and the number of electrochemically active site of the Li-doped nickel oxide and their corresponding electrochemical properties for the Li-doped nickel oxide film prepared by the ESD technique. The $\text{Li}_{0.1}\text{Ni}_{0.9}\text{NiO}$ film deposited at 200°C exhibits the maximum specific capacitance of 251 F/g with a high rate capability in 1 M KOH solution. This relatively high specific capacitance of this film was originated from its unique highly porous surface morphology and amorphous structure.

Key Words : Li-doped Nickel Oxide, Electrostatic Spray Deposition, Surface Morphology, Amorphous Structure

1 Introduction

Electrochemical capacitor has achieved much attention recently due to its high power density and excellent reversibility and long cycle life.¹⁻³⁾ Potential applications of electrochemical capacitors include power enhancement and cycle life improvement of primary power sources such as batteries and fuel cells with a hybrid form. Energy storage mechanisms of electrochemical capacitors are classified into two areas: (i) double-layer capacitance arising from the charge separation at the electrode/electrolyte interface (ii) pseudocapacitance arising from fast, reversible faradaic reactions occurring at or near a solid electrode surface.

Carbon materials with very high-surface area are widely used for double layer capacitors.⁴⁾ On the other hand, transition metal oxides with relatively high-surface-area, such as hydrous RuO_2 ,⁵⁾ porous NiO_x ,⁶⁻⁸⁾ CoO_x ⁹⁾ and MnO_2 ¹⁰⁾ have been identified as possible electrode materials for pseudocapacitors.

Nickel oxide is being considered as one of the promising potential electrode materials for pseudocapacitors. Up to now, the sol-gel process and electrochemical route, which were developed by K. C. Liu *et al.*,⁶⁾ and V. Srinivasan *et al.*,⁷⁾ respectively, have been reported as the methods for fabricating porous NiO_x electrode for pseudocapacitors. The nickel oxide electrodes made using both sol-gel technique and electrochemical route exhibit relatively large specific capacitance, ranging from 200 to about 250 F/g (from a single electrode) with excellent cycle life.⁶⁻⁸⁾ However, the sol-gel technique is a complicated multi-step process and difficult to control thickness of the film.⁷⁾ The electrochemical route for making

nickel oxide electrode is relatively inexpensive and highly controllable compared with the sol-gel process but it is difficult to deposit relatively large mass of active materials with a desirable composition. Poor adherence of active materials to the substrate also remains to be solved in the electrochemical route.

Recently, J. Schoonman *et al.*, have developed the electrostatic spray deposition (ESD) technique and applied it to prepare transition metal oxide films for various applications such as electrodes for rechargeable lithium-ion batteries, organic solar cells, catalysis, solid oxide fuel cells and gas sensors.¹¹⁻¹³⁾ As for the formation of nickel oxide electrode materials for pseudocapacitors, the ESD technique offers many interesting advantages over the known preparation methods.⁶⁻⁸⁾ Major advantages of the ESD technique for making metal oxide films are a simple set-up, high rates of deposition, one-step process to make oxide layers, binder free synthesis, good adherence of active materials to the substrate and easy control of composition and morphology of the deposited layers. Among these advantages of the ESD technique, morphology control is especially significant because it provides an extra possibility to enhance the performance of a pseudocapacitor and it is also attractive for device fabrication because of its one-step process. However, the ESD technique has many attractive points for making metal oxide films as described above, no attempt has been reported to produce metal oxide thin film electrode for pseudocapacitor applications.

Electrode materials for electrochemical capacitor should exhibit not only high surface area along with electrochemical reactivity in the given potential range but

also high electric conductivity of material itself, since the power loss of the pseudocapacitor is actually determined by the *ohmic IR* drop at significantly high power rate.¹⁴⁾ Stoichiometric nickel oxide, NiO, is a pale green solid of very low conductivity. On the other hand, Li-doped nickel oxide, $\text{Li}_x\text{Ni}_{1-x}\text{O}$, which is called a controlled valance semiconductor, has high electric conductivity compared with stoichiometric NiO. For example, for $x = 0.1$ the specific resistance at room temperature is about $1\ \Omega\text{cm}$ in comparison with the value of $10^8\ \Omega\text{cm}$ for stoichiometric NiO.^{15–16)} Much attention has been focused on the electrical properties of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ electrodes^{15–16)} but little study has been reported on the electrochemical properties of these $\text{Li}_x\text{Ni}_{1-x}\text{O}$ electrodes for pseudocapacitor applications.

In present study we carried out the synthesis of the porous Li-doped nickel oxide thin film for the pseudocapacitor application using the ESD technique. The crystal structure, surface morphology and electrochemical investigations were made on the Li-doped nickel oxide films.

2 Experimental

Li-doped nickel oxide films were prepared by means of the ESD technique. Ethanol solutions of $0.04\ \text{M}\ \text{Li}(\text{CH}_3\text{COOH}) \cdot 2\ \text{H}_2\text{O}$ and $0.04\ \text{M}\ \text{Ni}(\text{NO}_3)_2 \cdot 6\ \text{H}_2\text{O}$ were prepared separately. The solutions were well mixed in a desired molar ratio and these solutions were used as the precursors. Typically, the precursor solution for 10% Li-doped nickel oxide was achieved by mixing the ethanol solutions of $\text{Li}(\text{CH}_3\text{COOH}) \cdot 2\ \text{H}_2\text{O}$ and $\text{Ni}(\text{NO}_3)_2 \cdot 6\ \text{H}_2\text{O}$ with a molar ratio of Li: Ni = 1: 9. In this study, we prepared the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films with x values ranging from 0.05 to 0.3. In order to deposit Li-doped nickel oxide films by ESD technique, a high DC voltage of 12 kV is applied between a substrate and a syringe (Hamilton Gas Tight, U.S.A.) containing precursor solution at a proper flow rate (*e.g.* 2 ml/h) and the precursor solution is atomized at the tip of the needle generating a spray. The spray is attracted to the heated substrate by the electrostatic force and a thin layer of Li-doped nickel oxide is formed on the substrate surface. Pt coated silicon wafer or Pt coated alumina were used as substrates and weighed before and after the deposition, in order to calculate the weight of the deposit. The deposited mass was measured using microbalance (Sartorius Ultra-Microbalance S4, Germany) and the mass of deposit was in a range of 0.3 to 0.4 mg. The nozzle-substrate distance was about 4 cm and the deposition temperature was ranging from 200 to 350°C. Since the Li-doped nickel oxide electrodes deposited at temperatures lower than 200°C had poor adherence and easily peeled off from the substrate during the redox cycling in 1 M KOH solution, the minimum deposition temperature was fixed at 200°C.

Surface morphology was observed using a scanning electron microscope (SEM, Hitachi S-4200, Japan) and crystal structure was analyzed using XRD (RINT/DMAX-2500, Rigaku, Japan). Electrochemical measurements were done in three electrode electrochemical cell in which Li-doped nickel oxide thin film electrode prepared by ESD technique was used as the working electrode, a

platinum plate as counter and a saturated calomel electrode (SCE) as a reference electrode. Cyclic voltammetry was performed using a potentiostat/galvanostat (Solart-ron 1287, U. K.) to determine the electrochemical properties and specific capacitance of the Li-doped nickel oxide thin film electrode in 1 M KOH solution at room temperature. Typical cyclic voltammograms measured at the 100th cycle were given in Figs. 3, 5 and 6 in this study.

3 Results and Discussion

In this study, we investigated the electrochemical properties and specific capacitance of Li-doped nickel oxide with x values ranging from 0.05 to 0.3 in a $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film electrode (Figs. 6, 7). Based on these investigations, the maximum specific capacitance was obtained at $x = 0.1$ in a $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film electrode. Thus, the crystal structure, surface morphology and electrochemical investigations were focused on the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film. The ESD offers excellent control of overall stoichiometry of the deposited film by controlling the composition of precursor solutions.¹⁷⁾ Thus, the overall composition of the deposited film is assumed to be identical to the composition of precursor solution.

Figure 1 shows the XRD patterns of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ films on Pt coated alumina substrates, indicating the deposition temperature effect on the crystalline structure of this film. The XRD patterns for 200°C and 250°C were identical exhibiting only Pt and Al_2O_3 peaks corresponding to the substrate. Thus, the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ films deposited at temperatures below 250°C had an amorphous structure. However for deposition temperatures higher than 250°C, the XRD patterns exhibited the characteristic peaks of rock salt NiO at $2\ \theta = 37.3, 43.3$ and 63.0° . This indicates that the incorporated Li^+ ions are introduced into nickel oxide lattice and can be explained easily by the nearly identical ionic radii of Li^+ and Ni^{2+} ($0.68\ \text{\AA}$ for Li^+ and $0.69\ \text{\AA}$ for Ni^{2+}). Considering the XRD peak at

Fig. 1 XRD patterns of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{NiO}$ films deposited at different temperatures; (a) 200°C, (b) 250°C, (c) 300°C, (d) 350°C.

Fig. 2 Surface morphologies of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{NiO}$ films deposited at different deposition temperatures; (a) 200°C, (b) 250°C, (c) 300°C, (d) 350°C. (Magnification : $\times 3000$)

$2\theta = 37.3^\circ$ of Fig. 1 (c), (d), the intensity of this peak increased gradually with an increase in the deposition temperature from 300°C to 350°C indicating improved crystallinity.

Figure 2 shows the surface morphologies of layers deposited at different temperatures. Surface morphologies of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film deposited at temperatures higher than 250°C [Fig. 2(b), (c), (d)] were almost identical, exhibiting a dense layer with no visible cracks. It is to be notified that the morphology of the layer deposited at 200°C consists of a relatively dense bottom layer containing many dendritic agglomerates on the top, forming a highly porous structure. Since the pseudocapacitance is originated from the interfacial process, morphology control is important with respect to the specific capacitance of the Li-doped nickel oxide films. As shown in Fig. 2, morphology of the deposited film can be controlled by adjusting the deposition temperature in ESD technique.

In order to determine electrochemical properties of the deposited films, and to quantify the capacitance of the active material as a function of deposition temperature, cyclic voltammetric studies were performed with the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ films deposited at four different temperatures. Figure 3 shows cyclic voltammograms of these four films in 1 M KOH solution at room temperature. Potential was scanned between 0.0 V and 0.5 V (vs. SCE) in both directions at a sweep rate of 30 mV s^{-1} and the current response was measured. The curves were normalized to the current response for 1 g of active material. The shapes of four cyclic voltammograms in Fig. 3 showed mirror like images that are characteristic of a capacitive behavior. Although the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ films exhibit capacitive behavior, the current response is potential dependent in contrast to the potential-independent current response of an ideal capacitor. It is notable that the current response is increased with decreasing deposition temperature, and this indicates that the specific capacitance of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film would decrease inversely to the deposition temperature.

Fig. 3 Cyclic voltammograms (CVs) of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ films deposited at four different deposition temperatures. The curves were normalized to the current response for 1 g of active material; and the CV was measured in 1 M KOH with a sweep rate of 30 mV s^{-1} .

Due to the potential-dependent current response of nickel oxide film, the average specific capacitance is calculated using half the integrated area between the curves of the cyclic voltammograms within the potential range 0.0 to 0.5 V and then dividing by mass of the films.¹⁰⁾ This calculation corresponds to using average values of anodic and cathodic current density in the following equation;

$$C = \frac{1}{2 \cdot \Delta V \cdot M} \int_{V_{\text{initial}}}^{V_{\text{final}}} \frac{i}{(dV/dt)} dV \quad (1)$$

where M is mass of the electrode material, ΔV is the potential window, $V_{\text{initial/final}}$ is the starting/end potential in one cycle, i is the instantaneous current at a given potential and dV/dt is the potential sweep rate.

The specific capacitance of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ films as a function of the deposition temperature is shown in Fig. 4 and the specific capacitance decreased with the deposition temperature. The maximum specific capacitance of 251 F/g was achieved at 200°C and this is comparable to that of nickel oxide prepared by other methods.⁶⁻⁸⁾ Beyond 200°C, the specific capacitance decreased sharply from 120 F/g at 250°C to 50 F/g at 300°C and finally it reached 36 F/g at 350°C. It is noteworthy that the specific capacitance of the film deposited at 200°C was more than 2 times greater compared with that of the film deposited at 250°C. The films deposited at 200°C and 250°C were of amorphous phase as shown in Fig. 1. Considering the surface morphology of the films deposited at 200°C and 250°C in Fig. 2, the high specific capacitance of the film deposited at 200°C could be attributed to the highly porous surface structure of this film compared with the relatively dense layer of the film deposited at 250°C. Thus, the increase in the active surface area of the film deposited at 200°C would play an important role to increase specific capacitance over that of the film deposited at 250°C.

Although there was no significant change in the surface morphology of the film deposited at 250°C and 300°C, there exists a very large difference in the specific

Fig. 4 Effect of the deposition temperature on the specific capacitance of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{NiO}$ films. The specific capacitance was obtained from the cyclic voltammograms in Fig. 3 using Eq. (1).

capacitance of these films. The film deposited at temperature below 250°C had an amorphous structure. On the other hand, the film deposited at temperature higher than 250°C had a crystalline structure. In previous reports on the cobalt oxide prepared via sol-gel method,⁹⁾ the maximum specific capacitance was achieved with an amorphous structure. It was reported that the decrease in specific capacitance of the cobalt oxide with the calcination temperature was due to the decrease in active reaction sites with the calcination temperature. In this view point, the higher specific capacitance of the film deposited at 250°C than that of the film deposited at 300°C is probably due to the increase of the electrochemically active sites of the amorphous structure of the film deposited at 250°C . A small decrease in specific capacitance observed for the films prepared at 300°C and 350°C maybe ascribed to due to the decreased electrochemically active sites with an increased crystallinity. Considering the specific capacitance of the film deposited at the deposition temperatures higher than 200°C , the number of electrochemically active sites would highly depend on the crystalline structure. (*i.e.* deposition temperature). From these results, it can be seen that the deposition temperature had a significant impact on the structure, surface morphology and the number of electrochemically active sites of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film prepared by the ESD technique. It should be noted that ESD technique is excellent for making thin film electrode of nickel oxide with an amorphous structure in contrast to the nickel oxide electrodes with a crystalline structure prepared by the sol-gel method and electrochemical route.⁶⁻⁸⁾

Figure 5(a) illustrates a set of cyclic voltammograms of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film deposited at 200°C with a sweep rate, and a relation between anodic current from Fig. 5(a) and a sweep rate is shown in Fig. 5(b). In case of the hydrous ruthenium oxide prepared by sol-gel process, it does not exhibit capacitor-like behavior in its cyclic voltammogram at sweep rates higher than 50 mV s^{-1} . Its cyclic voltammogram is seriously distorted and hardly considered to that of typical electrochemical capacitors. Also, its specific capacitance decreased from 720 F/g at 2 mV s^{-1} to 250 F/g at 50 mV s^{-1} .¹⁸⁾ However, it was found

Fig. 5 (a) Cyclic voltammograms of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{NiO}$ film deposited at 200°C in 1 M KOH solution, and (b) sweep rate dependence of capacitive current.

that the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film electrodes prepared by the ESD technique maintains typical cyclic voltammogram of an ideal supercapacitor even at a high sweep rate of 100 mV s^{-1} and the average specific capacitance decreases only slightly with increasing scan rate. For example, the specific capacitance at a sweep rate of 30 mV s^{-1} decreased slightly at a sweep rate of 50 mV s^{-1} from 251 F/g to 241 F/g . This specific capacitance of $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ thin film is comparable to that of the hydrous ruthenium oxide electrode at a sweep rate of 50 mV s^{-1} . As shown in Fig. 5(b), the values of the current response in positive sweeps were found to be linearly proportional to the potential sweep rate, a behavior of an ideal capacitor. Similar results were also obtained on the cathodic current during the negative sweeps. In comparison with nickel hydroxide, where the current response were proportional to the square root of the sweep rate due to the H^+ diffusion into the bulk of the active material, this result indicates that the charge storage process of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film deposited at 200°C is controlled not by diffusion reaction but by surface redox reaction at active material/electrolyte interface. Thus, the electrochemical redox reaction of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film deposited at 200°C is kinetically facile and would exhibit high power density. This enables that this oxide can be applied in the applications that require high power output.

The electrochemical stability of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film prepared at 200°C was studied as shown in Fig. 6. As evident from Fig. 6, the current response in the cyclic voltammogram increased slightly during the first 100 cycles without significant shape change. Upon further cycling, an anodic and a cathodic current peak was visible at $0.34\text{ V}_{\text{SCE}}$ and $0.23\text{ V}_{\text{SCE}}$, respectively and grew gradually. However, the peaks became saturated at cycles over 200. It can be seen that the anodic peak current of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film prepared at 200°C after 300 cycling is proportional to the scan rate indicating that the electrochemical reaction is kinetically fast surface reaction. Similar observation

Fig. 6 Cyclic voltammograms of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film deposited at 200°C as a function of cycle number. The curves were normalized to the current response for 1 g of active material; and the CV was measured in 1 M KOH with a sweep rate of 30 mV s^{-1} .

could be seen in cathodic peak currents. However, cyclic voltammograms did not change with cycling for $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films with the Li content x greater than 0.15. Furthermore, no current peaks were observed in the cyclic voltammograms of $\text{Li}_x\text{Ni}_{1-x}\text{O}$ prepared at temperatures higher than 200°C irrespective of Li content.

Figure 7 shows the effect of Li concentration on the electrochemical properties of the Li-doped nickel oxide films deposited at 200°C in 1 M KOH solution. In Fig. 7, nickel oxide was not considered because the cyclic voltammogram of this oxide film deposited at 200°C was not capacitive but similar to that of nickel hydroxide in 1 M KOH solution. Its cyclic voltammogram showed an oxidation and a reduction current peak on its anodic and cathodic scan, respectively. The peak current was found to be linear to $(\text{sweep rate})^{1/2}$ indicating that electrochemical reaction involved in the pure nickel oxide film at 200°C prepared by ESD technique is a diffusion controlled process. The current response in Fig. 7 increased with Li concentration up to 10% but decreased with Li concentration beyond 10%. In order to clarify this feature, the specific capacitance of the deposited films at 200°C which was calculated using the equation (1) was plotted in Fig. 8 as a function of Li concentration. Similarly to the current response, the specific capacitance increased with Li concentration up to 10%, however, decreased abruptly with Li concentration beyond 10%. The decrease in the specific capacitance is due to the decrease in nickel content responsible for pseudocapacitance in the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film. However, the specific capacitance of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films does not change in a simple manner with a decrease in nickel contents in the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films.

One of the possible factors for the specific capacitance change of these $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films with Li concentration is surface morphology. Figure 9 shows surface morphologies of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films with Li concentration. Surface morphologies of the 5% and 10% Li-doped nickel oxide films showed relatively porous surface structure, consisting of a relatively dense bottom layer and many dendritic agglomerates on the top. It should be noted that the

Fig. 7 Cyclic voltammograms (CVs) of the Li-doped nickel oxide films as a function of Li concentration. The curves were normalized to the current response for 1 g of active material; and the CV was measured in 1 M KOH with a sweep rate of 30 mV s^{-1} .

Fig. 8 Effect of the Li concentration on the specific capacitance of the Li-doped nickel oxide films. The specific capacitance was obtained from the cyclic voltammograms in Fig. 6 using Eq. (1).

10% Li-doped nickel oxide film showed more porous surface structure than that of the 5% Li-doped nickel oxide film. And the highly porous surface structure of the $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film was converted into relatively dense surface structure with numerous incorporated small particles at Li concentrations higher than 15%. The surface morphology of the $\text{Li}_{0.2}\text{Li}_{0.8}\text{O}$ (not shown here) film was almost identical to that of the $\text{Li}_{0.3}\text{Li}_{0.7}\text{O}$ film. Thus, the large decrease in the specific capacitance of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films from $x = 0.1$ to $x = 0.15$ was due to both the change in surface morphology and Ni content. Further decrease in the specific capacitance at Li concentrations higher than 15% was probably due to the decreased Ni content. However, considering the large specific capacitance of the $\text{Li}_{0.05}\text{Ni}_{0.95}\text{O}$ and $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ films compared with the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film with x values higher than 0.15, and the small increase in the specific capacitance of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film with an increase of x values from 0.05 to 0.1, factors other than surface morphology would also contribute to improve their specific capacitance.

Ni^{3+} ions can be formed by the incorporation of monovalent atoms.¹⁵⁻¹⁶⁾ Due to the fact that Li^+ and Ni^{2+} have nearly same ionic radii, lithium can be easily doped into

Fig. 9 Surface morphologies of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films deposited at 200°C with Li concentration of (a) 5%, (b) 10%, (c) 15%, (d) 30%. (Magnification : $\times 3000$)

nickel oxide to certain limit and produce Ni^{3+} with the same amount of Li added to the system in order to maintain the charge balance of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film. Thus, the ratio of $\text{Ni}^{2+}/\text{Ni}^{3+}$ can be controlled by the Li concentration in the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film. K. C. Liu *et al.* suggested that the oxidation and reduction reactions of the pre-existing Ni^{3+} ions participated in the charge storage of the sol-gel derived nickel oxide,¹⁹⁾ however, the effect of the ratio of $\text{Ni}^{2+}/\text{Ni}^{3+}$ in nickel oxide on its specific capacitance was not assessed. The ratio of $\text{Ni}^{2+}/\text{Ni}^{3+}$, surface morphology and crystal structure are believed to be responsible for the specific capacitance of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films. The ratio of $\text{Ni}^{2+}/\text{Ni}^{3+}$ is being measured using X-ray absorption spectroscopy (XAS) and its role in improving the specific capacitance of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ films will be reported elsewhere.

4 Conclusions

Thin films of Li-doped nickel oxide for a pseudocapacitor electrode were successfully prepared by the ESD technique and we were able to control the morphology and crystal structure of the deposited film by simply adjusting the deposition temperature. Moreover, the surface morphology of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film changed with Li concentration. The $\text{Li}_{0.1}\text{Ni}_{0.9}\text{O}$ film deposited at 200°C exhibited the maximum specific capacitance of 251 F/g with a high rate capability in 1 M KOH solution. This relatively high specific capacitance of this film was origi-

nated from its unique highly porous surface morphology and amorphous structure. Further study is under progress to elucidate the role of $\text{Ni}^{2+}/\text{Ni}^{3+}$ in the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film, and to improve the specific capacitance of the $\text{Li}_x\text{Ni}_{1-x}\text{O}$ film using XAS.

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