

The Sol-Gel-Derived Nickel-Cobalt Oxides with High Supercapacitor Performances

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Nickel cobalt (Ni-Co) oxides with various Ni/Co ratios are synthesized by using a sol-gel process. Electrochemical performance, microstructure, morphology and BET surface area are found strongly related to Ni and Co concentration. Increasing Co concentration changes the oxide microstructure from NiO crystal dominate structure (Ni:Co = 1:1 and 1:2) to Co_3O_4 dominate structure (Ni:Co = 1:4 and 0:1). A maximum specific capacitance of 1539 Fg⁻¹ was obtained for Ni-Co (Ni:Co = 1:2) oxide at a current density of $1Ag^{-1}$, and this capacitance is similar to that of RuO₂. A systematic study shows that the Ni-Co oxide (1:2) has a meso-porous structure with a high BET surface area of ~ 315 m² g⁻¹ and porous size of ~ 4.7 nm, which is favorable for the charge/ discharge process of a supercapacitor.

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Supercapacitors, also known as electrochemical capacitors, have thousands times higher capacitance than conventional electrolytic capacitors, and much higher power density than batteries and fuel cells. They can complement batteries in electrical energy storage and harvesting applications, when high power delivery or uptake is needed. They can even replace batteries, with the great advantage of much shorter charging time, when the energy density or specific capacitance is significantly increased.¹ According to energy storage mechanisms, supercapacitors can be divided into two types: electrochemical double-layer capacitors (EDLC) and pseudo-capacitors. In the former, energy storage arises mainly from the separation of electronic and ionic charges at the interface between the electrode materials, typically carbon, and the electrolyte solution. In the latter, fast Faradic reactions take place at the electrode materials, typically metal oxides, at characteristic potentials like in batteries, and give rise to what is called pseudo-capacitance. Although the well developed carbon materials ($\sim 200 \text{ Fg}^{-1}$) for EDLC are commercially available, other materials with higher capacitance are always desirable.² Transition metal oxides with various oxidation states are very promising candidates for the next generation high capacitance supercapacitors. They can have high pseudo-capacitance, high power density, energy density, mass density and cycle stability. Among these transition metal oxides, ruthenium oxide (RuO_x) with a specific high capacitance up to 1580 Fg^{-1} (Ref. 3) is widely studied in the past 30 years.⁴ However the high cost of RuO_x limits it from commercialization except in some special applications. It is of great interest in having cheaper metal oxides for high capacitance supercapacitors.

To find cheaper metal oxides, various transition metal oxides have been investigated, such as Co₃O₄, MnO₂, NiO, V₂O₅, etc. Among them, nickel oxide has shown very high specific capacitance, low cost, low toxicity and environment friendliness, but with relatively low cyclic reversibility.⁵ Cobalt oxide, on the other hand, has high redox activity and good reversibility, but the specific capacitance is relatively low.⁶ Nowadays because of more and more advantages of Nickel and Cobalt, both of them attracted more attention. For instance, Zhang and Fang found a general strategy to prepare Pt 3d-transition metal (Co, Ni) nanotubes for use in fuel cells.⁷ Meanwhile previous research results indicated that doping Co could enhance NiO electrochemical reversibility and conductivity.⁸ Hu et al.⁹ prepared hydrous Ni-Co oxide with an amorphous structure [denoted as $a-(Co + Ni)(OH)_2 \cdot nH_2O$] by using anodic deposition method and obtained a specific capacitance of $\sim 730 \text{ Fg}^{-1}$. He et al.¹⁰ and Liu et al.¹¹ prepared Ni-Co oxide/Al-layered double hydroxides composite composites, Ni-Co oxide/TiO2 nanotube composites and Ni-Co oxide/carbon nanotube composites by using anodic deposition method and obtained the highest specific capacitance of ~840 Fg⁻¹. More recently, Wei et al.¹² prepared a spinel nickel cobaltite (NiCo₂O₄) aerogel with the highest specific capacitance of ~1400 Fg⁻¹ after annealing the as-prepared sample at 200°C for 5 h. However, the synthesis and processing methods reported so far are not practical for commercial production because they are either slow in the growth of very thin layer on thick substrates or expensive for large scale industrial production. Furthermore, a comprehensive understanding of the relationship between the electrochemical behavior and the microstructure of the binary Ni-Co oxides for supercapactors is still lacking. Efforts are necessary to find more suitable syntheses methods for cheap and nanostructure Ni-Co oxides with a high capacitor performance. Furthermore, it is necessary to study the microstructure and performance of Ni-Co oxide composites with different Ni/Co ratios in depth.

In this work, Ni-Co oxides are prepared by a sol-gel method that can be suitable for large scale commercial production. It will be shown that the sol-gel process enables to prepare mesoporous oxides with high specific surface area and 3D network having an average pore size of several nanometers. The effect of Ni/Co molar ratio on the crystalline structure and capacitive behaviors of the oxides are investigated. Ni-Co oxide with a high specific surface area (maximum 315 m^2g^{-1}) is achieved when the Ni/Co molar ratio is 1:2. The resulting Ni-Co oxide exhibits a high maximum specific capacitance of 1539 F g⁻¹under constant current discharge (current density at 1 Ag⁻¹) in 1 M KOH electrolyte.

Experimental

Ni-Co oxides preparation.-All the chemicals used are of analytical grade without further purification. An aqueous solution of Na₃C₆H₅O₇·2H₂O, NaOOCCH₃, NiSO₄·6H₂O and CoSO₄·7H₂O (Sample A: pure NiSO4·6H2O, Sample B: 1:1 cationic ratio of Ni:Co in solution, Sample C:1:2 cationic ratio of Ni:Co in solution, Sample D:1:4 cationic ratio of Ni:Co in solution, Sample E: pure CoSO₄·7H₂O) was kept at 80°C in water bath under constant stirring. 3M KOH was added dropwiselyinto the solution until the pH value reached 12. The solution was kept at 80°C for 2 h, and then at room temperature for 24 h. The resulting suspension was centrifuged and rinsed repeatedly with deionized water and ethanol. The gel was then heated to 70°C and held there for 12 h, and then grinded into fine powders and kept at 200°C in air for 12 h. The obtained Ni-Co oxides for various cationic ratio Ni/Co solutions are referred to as Ni-Co oxides (the cationic ratio of Ni/Co in solution); for example, Ni-Co oxide (1:2) indicates that the Ni-Co oxide composite is prepared with a 1:2 cationic ratio of Ni:Co in the solution.

Electrode preparation.—70 wt % of the prepared active Ni/Co oxide powder, 25 wt % of acetylene black, and 5 wt % of polytetra-fluoroethylene (PTFE) were mixed together in ethanol, and ultrasonic was used to ensure uniform mixing. Then the mixed slurry

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was spread onto a piece of Ni foam of weight (m_1) within an area of $\sim 0.25 \text{ cm}^2$. The electrode was then dried at 70°C in air for 2 h, pressed at 8 Mpa, kept at 140°C in air for 12 h, and weighed (m_2) . The weight of the active material was calculated by $(m_2-m_1) \times 0.7$, which was about 4–6 mg for each of our samples.

Characterization and electrochemical tests.—Transmission electron microscopy (TEM, JEOL 2000FX) with energy dispersive X-ray (EDX) analyzer was used to characterize the crystal structure and composition of the materials. The surface morphology was determined by scanning electron microscope (SEM, Zeiss SUPRA 40). Specific surface area, pore volume and width were measured by nitrogen adsorption/desorption using Brunauer-Emmet-Tell (BET, Micromeritics ASAP2020) method. All electrochemical measurements were carried out in a three-electrode arrangement with the prepared electrode as working electrode, a platinum plate as counter electrode and a saturated calomel electrode (SCE) as reference electrode in 1 M KOH electrolyte. Electrochemical performance was evaluated by cyclic voltammetry (CV) and galvanostatic charge/discharge tests (Solartron S1 1287).

Results and Discussion

Characterization of the Ni-Co oxides.—The molar ratios of Ni/Co in these Ni-Co oxides were determined by EDX. The results are shown in Table I. It is noted that for Ni-Co oxide samples 1:1, 1:2 and 1:4, the actual Ni/Co molar ratios are 1:0.8, 1:1.4 and 1:4.3, respectively.

Figure 1 shows XRD patterns of five samples. From the XRD pattern, we can find that it is Co₃O₄ structure (PDF#09-0418: space group Fd-3m, Cubic, lattice constant 0.8084 nm) for the Ni:Co = 0:1 sample. Meanwhile the diffraction peaks of the Ni-Co oxides (1:4) also indicate that it has the similar Co₃O₄ structure. However for the Ni-Co oxides (1:2), the diffraction peaks are strongly different from the Co₃O₄ structure, and they can be indexed as NiO phase (PDF#65-2901, space group Fm-3m, Cubic, lattice constant 0.4195 nm). For the Ni-Co oxides (1:1), there are inconspicuous humps instead of obvious peaks. NiO and Ni(OH)2 (PDF#02-1112, space group P-3m1, hexagonal, lattice constants a = b = 0.311 nm and c = 0.466 nm) peaks fall in the ranges of the humps. The same result could be obtained from the XRD pattern of the Ni:Co = 1:0 sample. Additionally the sharp peaks of the XRD pattern of pure Ni sample may be caused by impurity noises. In order to further understand the structure of these oxides, we also take TEM images and diffraction patterns.

Figure 2 shows electron diffraction patterns and TEM images of the five samples. The diffraction rings of the corresponding crystal planes are indexed in the patterns. The ring patterns demonstrate polycrystalline nature of the five samples. The selected area diffraction pattern of Ni:Co = 1:0 sample correspond to NiO. For samples of Ni-Co oxides (1:1 and 1:2), the diffraction patterns are very similar to that of NiO, and the rings belong to NiO (111), (200), (220), (311) and (222). The diffraction pattern of Ni-Co oxide (1:4) is close to that of Co₃O₄, and the rings appear belonging to Co₃O₄ (111), (220), (311)/(222), (400), (422), (511), (440), (620)/(533)/(622)/(444), (642). These results are in agreement with the XRD results. Based on theoretical calculation of the ring radius of cubic structure

Table I. Ni/Co Molar ratio, specific surface area, pore width and cumulative pore volume of five samples Ni-Co oxides 1:0, 1:1, 1:2, 1:4 and 0:1.

Ni/Co Molar Ratio in solution	1:0	1:1	1:2	1:4	0:1
Ni/Co Molar Ratio in sample Specific Surface Area (m^2g^{-1}) Average Pore Width (Å) Cumulative Pore Volume (cm^3g^{-1})	1:0 377.68 29.80 0.32	1:0.8 329.7 31.69 0.38	1:1.4 315.10 47.65 0.55	1:4.3 99.42 41.28 0.17	0:1 61.26 55.76 0.12



Figure 1. (Color online) XRD patterns of pure NiO, Ni-Co oxdie (1:1), Ni-Co oxdie (1:2), Ni-Co oxide (1:4), and pure Co_3O_4 .

NiO (a = b = c = 0.4176 nm) and cubic structure Co_3O_4 (a = b = c = 0.8085 nm), the radii of 111, 200, 220 and 311 rings of NiO are only 1% different from 311, 400, 440 and 533 rings of Co_3O_4 , respectively. We notice that the 111, 200, 220 and 311 NiO rings for Ni-Co oxides (1:2) shown in Fig. 2c are slightly brighter than those rings of NiO (Fig. 2a), which may suggest the co-existence of 311, 400, 440 and 533 rings of Co_3O_4 in the diffraction patterns. The 311, 400, 440 and 533 rings are slightly brighter in Fig. 2d for Ni-Co oxides (1:4) than those of Co_3O_4 (Fig. 2e), which may suggest the coexistence of the 111, 200, 220 and 311 NiO rings in Fig. 1c. Therefore, the possibility of the existence of Co_3O_4 crystal in Ni-Co oxide (1:1 and 1:2) and NiO crystal in Ni-Co oxide (1:4) cannot be excluded.

The dark field TEM images, which were taken using the smallest objective aperture at a small portion of the strongest diffraction pattern rings, reveal that the sizes of bright patches in Figs. 2b–2d are smaller than those in Figs. 2a and 2e. Because one diffraction spot corresponds to a series parallel crystal planes, the size of a bright patch in the dark-field image can represent the size of a crystallite with straight lattice planes. Such results suggest that crystallite sizes in the Ni-Co oxides are smaller than those in Ni(OH)₂/NiO and Co₃O₄ samples, which may have effect on supercapacitor performance.

Electrochemical Testing of Ni-Co oxides.—Cyclic voltammetry tests within a 0.0–0.5V potential range (vs. SCE) at a scan rate of 1 mV s⁻¹ were performed in 1M KOH electrolyte at room temperature. Figure 3 shows the CV curves of the five samples. A pair of redox peaks can be observed in each CV curve, which indicates a pseudo-capacitance characteristic. The CV curve of pure NiO shows two obvious peaks. The cathodic peak occurs at around 0.36 V and the anodic peak occurs at around 0.22 V. These two peak positions are in consistent with those of Ni(OH)₂/NiO reported previously¹³ and the corresponding Faradic redox reaction is

$$NiO + OH^- \leftrightarrow NiOOH + e^-$$
 [1]

$$Ni(OH)_2 + OH^- \leftrightarrow NiOOH + H_2O + e^-$$
 [2]

For pure Co_3O_4 , a pair of broad and less obvious peaks can be seen at around 0.39 and 0.35 V, in agreement with those of Co_3O_4 reported in literature¹⁴ and can be attributed to the Faradic redox reaction

$$Co_3O_4 + OH^- + H_2O \leftrightarrow 3CoOOH + e^-$$
 [3]



Figure 2. Electron diffraction patterns and TEM images of (a, a') pure NiO; (b, b') Ni-Co oxide (1:1); (c, c') Ni-Co oxide (1:2); (d, d') Ni-Co oxide (1:4) and (e, e') pure Co₃O₄.

In the CV curves of the three Ni-Co oxides (1:1, 1:2, and 1:4), the redox peaks are broadened with an increase in Co, and both anodic and cathodic peaks shift to the negative direction. It is better to admit that we are still unable to provide an explanation on the broadening and left shift of the redox peaks, however, such phenomena may suggest that the samples are not a simple mixture of NiO and Co₃O₄. Changes in valence of metal ions or/and oxygen content in the compound, which cannot be obtained from XRD and TEM, may also be important to cause redox peaks shift and broadening. However, XPS characterization of our samples does not show obvious difference in the peak positions for Co and Ni atoms/ions for different samples, therefore, XPS results cannot reveal the cause of the redox peak shift and broadening. Another possible reason for the redox peak shift and broadening may be because Ni is partly substituted by Co with different valence number so that the electronic state and the electrochemical properties of oxide materials are changed. However, to determine the substitution is not an easy task and we are unable to perform such a measurement. Although it is



Figure 3. (Color online) Cyclic voltammograms of pure NiO, Ni-Co oxide (1:1), Ni-Co oxide (1:2), Ni-Co oxide (1:4), and pure Co_3O_4 recorded in 1 M KOH solution at a scan rate of 1 mVs⁻¹.

impossible to find experimental evidence to reveal the reasons for the phenomena observed, the experimental observations and the proposed possible reasons may be good starting points in further research for a deeper understanding of such a materials system and the electrochemical behavior. It is further interesting to notice that the curves of Ni-Co oxides, in comparison with the CV curve of Ni(OH)₂/NiO, are closer to rectangular shape that is the characteristic shape of carbon and the expensive RuO₂ supercapacitors. Furthermore, the area enclosed by the CV curve is much bigger than that of Co_3O_4 . Such results suggest that the Ni-Co oxides are more favorable for supercapacitor application. The exact capacitance values are determined from discharging curve shown below.

Figure 4 shows the charge/discharge curves at a current density of 1 A g^{-1} within the potential window of 0.0–0.4 V in 1 M KOH electrolyte for the five samples. When the electrode starts to discharge, a potential drop can be seen from the curves. Such a phenomenon is due to the electrode polarization at a high current density. The specific capacitance can be calculated using Eq. 4

$$C = \frac{I \times \Delta t}{m \Delta V}$$
[4]



Figure 4. (Color online) The charge/discharge curves of Ni(OH)₂/NiO, Ni-Co oxide (1:1), Ni-Co oxide (1:2), Ni-Co oxide (1:4), and pure Co_3O_4 recorded in 1 M KOH solution at a current density of 1 Ag⁻¹.

where C (Fg⁻¹) is specific capacitance, I (A) is discharge current, Δt (s) is discharge time, m(g) is mass of the active electrode material, and ΔV (V) is potential change during discharge (set as 0.4 V). The specific capacitance is calculated to be 1289, 1410, 1539, 1060 and 361 F g^{-1} for Ni(OH)₂/NiO, Ni-Co oxide (1:1), Ni-Co oxide (1:2), Ni-Co oxide (1:4), and pure Co₃O₄, respectively. Such results are in consistent with the IV curves shown in Fig. 3. When the ratio of Ni and Co is 1:2, we can obtain the maximum specific capacitance value 1539 F g^{-1} , which is much closer to the value of RuO_x. However based on Eqs. 1 and 3, the theoretical specific capacitance is calculated to be 3229 and 1001 F g⁻¹ for NiO and Co₃O₄, respectively. Therefore the specific capacitance of Ni-Co oxide should reduce with increasing Co concentration. However, the experiment results show that the Ni-Co oxide (1:2) has the highest specific capacitance among the five samples, which will be discussed further later. Also interestingly, the discharge curves become more symmetrical to their charge curves and more linear with an increment of Co in the Ni-Co oxide. The linear discharging curve is characteristic of supercapacitor behavior in contrast to the battery behavior.⁴ For sample Ni-Co oxides 1:2 and 1:4, the CV curve shape is close to those of carbon and RuO₂, and the specific capacitance is much higher than that of carbon and similar to that of RuO₂. Due to the high specific capacitance and the much lower price of Ni and Co than Ru, the Ni-Co oxide supercapacitor has its unique advantage and may be a very promising candidate for the next generation of commercial high capacitance supercapacitors.

SEM images show porous morphologies of these samples. For the Ni:Co = 1:0 NiO sample (Fig. 5a), we can find that most of pores are mesopores, which can possibly be one reason why Ni(OH)₂/NiO has a much higher surface area and specific capacitance than that of Co₃O₄. With increasing of Co concentration, the ratio of macrospores is increased (Figs. 5b, 5c, and 5d), which may contribute to the decreasing of specific surface area of samples. However SEM cannot tell quantitative size distribution of the microspores in these samples, further characterization was carried out.

In order to give quantitative distribution of the microspores in these samples, nitrogen adsorption/desorption experiment was carried out. BJH (Barrett-Joyner-Halenda) calculation with N₂ adsorption–desorption isotherm desorption branch was adopted. Figure 6 shows the BJH adsorption pore distribution of samples Ni-Co (1:0), Ni-Co (1:1), Ni-Co (1:2), Ni-Co (1:4), and Ni-Co (0:1). The precise positions and distributions of the 3–4 nm peaks may be doubtful due to the use of desorption branch for the calculation, but the qualitative results and trend are meaningful. The majority of the pores fall in the size range of 2–10 nm, which is favorable for supercapacitor applications due to the interconnected pores forming channels easy for electrolyte to diffuse into the material.¹² An increase in the electrode-electrolyte interfacial area enables more activities of OH⁻



Figure 5. SEM images of (a) Ni(OH)₂/NiO (b) Ni-Co oxide (1:2) (c) Ni-Co oxide (1:4) (d) pure Co_3O_4 .



Figure 6. (Color online) BJH adsorption pore distribution of samples with Ni:Co equal to 1:0 (Ni(OH)₂/NiO), 1:1, 1:2, 1:4 and 0:1 (Co₃O₄).

insertion and extraction, and thus increases the material utilization in supercapacitor functioning. Pore size distribution maximum shifts to a lager pore size with increasing Co concentration. The specific surface area and cumulative pore volume, determined from BET calculation, for different samples are listed in Table I. It is seen that the specific surface area decreases with an increase in Co content in the Ni-Co oxides sample, while the cumulative pore increase from sample 1:0 to 1:4, and then decreases. The trend in mean pore width may possibly be due to the co-existence of big and small pores in the Ni-Co oxides samples.

The reasons for Ni-Co oxide (1:2) having the maximum specific capacitance value are further discussed here. If we only consider the electrochemical double-layer mechanism or the adsorption of cations on the surface of the active material,¹⁵ the capacitance should follow the trend of surface area, the sample Ni:Co = 1:0 should then have the highest specific capacitance according to the data in Table I. Furthermore, NiO has a much higher theoretical specific capacitance than that of Co₃O₄, also indicating that the sample Ni:Co = 1:0 should have the highest capacitance. However, sample Ni-Co oxide (1:2) has the highest capacitance, even though it does not have the biggest surface area and the highest NiO or Ni(OH)2 concentration. This phenomenon should be related to the utilization of these oxides during the charge/discharge process. Pore size and pore volume are also important factors for determining the surface utilization besides the specific surface area. If the pore size is big. the surface area can be small and thus the capacitance is low; however, too small a pore width will limit ions penetrating into the material to cause a low capacitance as well.¹⁶ As shown in Table I, Ni-Co oxide (1:2) has large pore width and cumulative pore volume among the five samples. The large pore width and volume may allow ions penetrating into the pores and react with the material more easily and gives rise to an increase in the surface utilization. In addition, pore size distribution in Ni-Co oxides may also play roles, the capillary force would hold the electrolyte and prevent it from over flooding due to the small size of the pores (<10nm).¹⁷ Furthermore, Pseudo-capacitance mechanism can be another factor in affecting capacitor performance and capacitance. Both the curved instead of linear shape of the charge/discharge profiles and the redox peaks in CV curves suggest a pseudo-capacitive characteristic. Redox peaks in CV curves are caused by the Faradaic reactions (electrochemical reactions) between active materials in electrodes and electrolytes. The capacitance from Faradaic reactions belongs to a pseudo-capacitance. Therefore, in addition to surface utilization, materials reactivity also play important role. The improvement in the capacitance by adding certain amount of Co ions into the NiO matrix may also may be that Co³⁺ takes some sites of Ni²⁺ in NiO



Figure 7. (Color online) Charge/discharge curves of Ni-Co oxide (1:2) recorded in 1 M KOH electrolyte at different current densities of 1, 2, and 5 A g^{-1} .

crystal lattice, which induces additional positive defection. The probability of protons transporting is thus increased and electrons can escape from Ni much more easily, so that the chemical activeness of electrode material is improved. Furthermore, Co^{3+} could also improve the conductivity of electrodes, reduce the inner resistance of the chemical reactions, and improve reversibility of the electrode reactions.¹⁸

Figure 7 shows the Ni-Co oxide (1:2) charge/discharge curves at different current densities within the potential window of 0.0–0.4 V in 1 M KOH solution. The specific capacitance is calculated to be 1539, 1447 and 1136 F g⁻¹ at 1, 2, and 5 Ag⁻¹, respectively. An increase in the current density leads to a decrease in specific capacitance as expected, because some of the ions have not participated in the reaction due to the slow diffusion rate and electron transfer rate at a high current density. In order to get a better understanding of the cyclic behavior of Ni-Co oxide (1:2), another experiment was carried out with the electrode subjected to charge/discharge over 2000 cycles at a current density of 5 Ag⁻¹ between 0.0 and 0.4 V at room temperature. There are two reasons for our using a high charge/discharge current of 5 A/g, rather than 1 A/g, in the 2000



Figure 8. Dependence of specific capacitance of Ni-Co oxide (1:2) on number of cycles.

cycle test. One is that we want to see the supercapacitor performance at a high charge/discharge current, because it is well known that a high charge/discharge current is very harmful to the life of a battery. Another reason is that 2000 charge/discharge cycles at 1 A/g takes too long (~ 670 h) due to the high capacitance or high charge storage ability of the sample, and it takes only ~ 110 h for 2000 cycles at 5 A/g. The results are shown in Fig. 8. It can be seen that the discharge specific capacitance increases sharply in the initial 240 cycles. This initial increase is due to the mesoporous structure, because electrodes were needed to activate fully. Similar phenomena were reported by other groups.^{12,17} Luo et al.¹⁷ observed a capacitance increase in the initial 300 cycles for Mn-Ni-Co oxide composites and they explained that such a phenomenon was caused by a gradual penetration of electrolyte into the active material. After reaching the maximum at around 240 cycles, it begins to decrease and stabilizes after around 1000 cycles. The capacitance retention after 2000 cycles is about 47%. The fade of capacitance of Ni/Co oxide is mainly due to the peel off the active materials form electrode during charging and discharging process, as precipitates can be found in the bottom of container.

Conclusions

In this work, Ni-Co oxides with different compositions were successfully prepared by a sol-gel method. The microstructure and nanostructure of these marterials are found strongly influenced by Ni and Co concentrations. Increasing Co concentration changes the sample from NiO dominant structure (Ni: Co = 1:2) to Co₃O₄ dominant structure (Ni: Co = 1:4) with a reduced BET surface area. The electrochemical properties of the Ni-Co oxides are found being strongly affected by the Ni/Co ratio, microstructure, morphology, and mesoporosity. A maximum specific capacitance of 1539 Fg⁻¹ was obtained for Ni-Co oxide (1:2) at a charge/discharge current density of 1 Ag⁻¹, such a capacitance is similar to the maximum value of the expensive RuO₂. Its cyclic reversibility and performance under large discharge current are also good.

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