Porous NiO/graphene composite thin films as high performance anodes for lithium-ion batteries

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Abstract: Porous NiO and NiO/graphene (NiOG) thin film electrodes were prepared by electrostatic spray deposition (ESD) technique and investigated as anodes for lithium ion batteries. The porous NiO structure was designed to better buffer the mechanical stress induced by the volume change of NiO as well as inhibit the aggregation of nanoparticles during conversion reaction. Aiming to facilitate better reaction kinetics compared to pure NiO electrode, graphene nanoplates were added to form NiOG composite film where additional graphene could be helpful for the electron transfer as conductive medium. As a result, porous NiOG composite thin film electrode exhibits high rate capability (759, 774, 614, 447, 243 and 104 mAh g⁻¹ at 0.1, 0.2, 0.5, 1, 2, and 5 A g⁻¹, respectively) and excellent cycling performance (no capacity decrease for 500 cycles at 0.5 A g⁻¹). From analyzing cyclic voltammetry (CV) curves, rate and cyclical performance, and electrochemical impedance spectroscopy (EIS), it was concluded that NiOG composite electrodes exhibited enhanced electrochemical performance compared to NiO electrodes.

Keywords: Nickel oxide; graphene; electrostatic spray deposition; conversion reaction; lithium ion battery

1. Introduction

There is an urgent need to develop high performance lithium ion batteries (LIBs) as the energy storage source for electric vehicles (EVs), hybrid electric vehicles (HEVs) and mobile electronic devices [1-4]. As one of the transition metal oxides (TMOs), nickel oxide (NiO) is considered as a promising anode candidate for LIBs owing to its high theoretical capacity (718 mAh g^{-1}) compared to typical commercial graphite anode (theoretical capacity: 372 mAh g^{-1}) [5]. Moreover, the low cost, nontoxicity, environmental benignity, and natural abundance make it more appealing [6]. Despite these promising properties, however, some of the issues hindered its real life application, including: 1) large volume changes resulting from phase change and structural re-organization; 2) low round-trip energy density caused by polarization induced hysteresis; 3) low Coulombic efficiency for the first charge-discharge cycle; 4) low electronic conductivity which limited high rate performance; 5) relatively high working voltage as compared to graphite and other alloying anodes which leads to low cell energy density.

A variety of strategies have been developed to circumvent these challenges. For example, fabrication of nanostructured materials with various morphologies, such as nanoparticles [9], nanowires [10], nanosheets [11] and nanotubes [12], shows great promise in enhancing electrochemical performance. On the one hand, shorter diffusion path for both electrons and ions can be achieved by using nanomaterials leading to improved conductivity and rate capability. On the other hand, large volume change during cycling could be buffered and accommodated using the nanostructures. Nevertheless, a large surface area of nanostructured materials leads to severe side reactions and SEI formations, especially for the first several cycles, which typically cause huge irreversible capacities [5]. Meanwhile, composite materials like NiO/carbon (such as: graphene) [13-16] and NiO/metal [17] are being proved to be promising with improved the cycle life and rate performance due to the ability to provide good kinetics and maintain structural integrity during the cycling. For example, improved cycling stability and rate capability of NiO electrode were achieved by additional graphene due to enhanced electronic conductivity. However, for most of the cases, the

1 current densities are kept less than 2 A g^{-1} with limited cycles (<400 cycles).

2 Here in this study, porous NiO/graphene thin composite films were fabricated via electrostatic
3 spray deposition (ESD). ESD is a simple and versatile technique for fabricating variety of
4 morphologies, such as thin-films, porous and fibrous structures, and single or multi-component
5 composite films [18-21]. By carefully controlled experimental conditions, 3D porous NiO electrodes
6 and NiO/graphene (NiOG) composite electrodes were prepared. Both structure characterization and
7 electrochemical characterization were conducted. Here, we are trying to buffer the stress, decrease the
8 diffusion length, and improve the rate performance by creating porous structured NiO/graphene
9 composite electrodes using electrostatic spray deposition (ESD). The specific discharge capacities of
10 porous NiOG composite were obtained as 759, 774, 614, 447, 243 and 104 mAh g^{-1} at 0.1, 0.2, 0.5, 1,
11 2, and 5 A g^{-1} , respectively. The results show that NiOG composite electrode exhibits high reversible
12 capacity, long cycle life and excellent rate capability.

13 **2. Experimental**

14 **2.1. Sample preparation and characterization**

15 NiO and NiO/graphene composite anodes were synthesized through a home-made ESD system
16 [18-21]. For a typical ESD set-up, it contains a nozzle connected with a syringe that provides the
17 precursor through a pump, a heated substrate, and a high voltage DC power supply providing high
18 voltage between the nozzle and substrate. During the deposition process, a high DC voltage is applied
19 to accelerate atomized liquid precursor droplets at the tip of the nozzle; the charged droplets will form
20 aerogels during travelling to the substrate through gradual solvents evaporation; the residual solvents
21 evaporation and precursor decomposition occur when the aerogels reached the heated substrate and
22 finally form the designed thin film structures. The structures and morphologies of the resulting film
23 can be controlled by changing the deposition conditions, such as applied voltage, feeding rate,
24 precursor concentration, substrate temperature, needle to substrate distance, and types of solvents, etc.
25 The electrodes derived from ESD usually have low active material loading with better high rate
26 capability due to the porous nature. It could be used in some miniaturized energy storage and power

1 generation systems, such as microbatteries, where due to the limited footprint area the specific areal
2 capacity (mAh cm^{-2}) is more critically considered.

3 In brief, in order to synthesize NiO samples, nickel acetate ($\text{Ni}(\text{CH}_3\text{CO}_2)_2 \cdot 4\text{H}_2\text{O}$) was dissolved in
4 a mixture of ethanol and 1, 2-propanediol in a 1:1 volume ratio as precursor solution. Graphene
5 nanoplates were purchased from Cheaptubes Inc. with a specific surface area of $600\text{--}750 \text{ m}^2 \text{ g}^{-1}$ and
6 average platelet diameter of less than $2 \mu\text{m}$. In order to synthesize NiOG composites, 3.2 wt %
7 graphene nanoplates was added to the precursor nickel acetate and organic solutions which will
8 produce 10 wt % graphene in the total composite at the assumption of complete decomposition of
9 nickel acetate into NiO. Ti foil was used as a substrate for the XRD characterization with prolonged
10 deposition time (6 hrs). All other electrodes for the electrochemical test and SEM characterization
11 were deposited on porous Ni foam. The prepared precursor solution was atomized at a high DC voltage
12 of $6.0\text{--}8.0 \text{ kV}$. The nozzle-to-substrate distance was kept to be 4-5 cm. The deposition temperature was
13 controlled at 250°C . The deposition time was controlled to be 2 h with an average loading of about 1
14 mg/sample . Each sample was individually weighted using Mettler-Toledo AB135-S/FACT balance
15 with accuracy of 0.01mg .

16 2.2. Material characterization

17 The X-ray diffraction patterns were collected using a D-5000 diffractometer operated at 40 kV and
18 40 mA, using Cu-K α radiation ($\lambda=0.154056 \text{ nm}$) with a scanning rate of 1° min^{-1} between 10° and 90° .
19 N_2 adsorption-desorption isotherms were collected by Micromeritics instrument TriStar II at 77 K. The
20 morphology of the electrodes was investigated using a field emission-scanning electron microscope
21 (JEOL 6335FE-SEM).

22 2.3. Electrochemical characterization

23 Electrochemical test cells (2032 coin cells) were assembled in an argon filled VAC Nexus I glove
24 box. The NiO and NiOG electrodes were used as working electrodes; lithium foils were used as
25 counter and reference electrodes. Celgard 2400 microporous polypropylene films were used as
26 separators. The electrolyte was 1 M lithium bis(perfluoroethylsulfonyl)imide dissolved in ethylene
27 carbonate (EC): diethyl carbonate (DEC): ethyl methyl carbonate (EMC) in the volume ratio of 1:1:1.

Cyclic voltammetry (CV) was performed using Bio-logic versatile multichannel potentiostat (VMP3) at the scan rate of 0.2 mV s^{-1} . Charge-discharge characteristics were tested galvanostatically between 0.02 and 3.0 V at room temperature using a NEWARE BTS-610 Battery Test System. Impedance spectra were obtained using VMP3 at the open circuit voltage with an ac oscillation of 10 mV amplitude over the frequencies from 100 kHz to 0.1 Hz. The EIS data were fitted using Z-fit function in EC-Lab (V10.40) software. All the voltages mentioned in this paper are vs. Li^+/Li . The cell disassembly was carried out in the glove box and the working electrodes were washed in DEC/EMC solution. Two sets of samples for each electrode were tested for CV and rate capability evaluation. Representative CV curves for both samples were presented. The deviation of the capacity for rate capability test was within 5 % for both electrodes and the results with higher values were presented in this study. The charge and discharge processes correspond to Li^+ extraction and insertion from electrodes, respectively. Discharge capacity was used to show the specific capacity in rate capability and cycle life tests. The specific capacities were calculated based on the mass difference before and after materials deposition on the substrates.

3. Results and Discussion

The XRD patterns of as-deposited NiO and NiOG films prepared under the same deposition conditions but on a Ti foil are shown in Fig. 1(a). For NiO, in addition to those peaks from the Ti substrate, it clearly shows the three major diffraction peaks from NiO sitting at 2θ of 37.2° , 43.2° and 62.9° , which are indexed to (101), (012) and (220) planes of cubic structure of NiO. However, relatively low intensity NiO diffraction peaks were observed for NiOG samples. The broad NiO diffraction peaks from both NiO and NiOG indicate that the films are essentially amorphous, which is primarily attributed to the low deposition temperature (250°C) and commonly observed in our previous reports [18-20, 22]. Fig. 1(b) exhibits the BET test results for powder samples scratched off from the substrates. The BET surface areas of NiO and NiOG are 64.70 and $75.24 \text{ m}^2\text{g}^{-1}$, respectively. NiOG electrode exhibits higher surface area than NiO electrode due to the high surface area graphene. The adsorption-desorption curves of NiO and NiOG show obvious H2 type hysteresis loops which are attributed to the pore connectivity effect from relatively uniform channel-like pores [23].

1

2 Figure 1. (a) XRD spectra of as deposited NiO and NiOG thin films on Ti foil; (b) Nitrogen
3 adsorption-desorption curves of NiO and NiOG powder samples scratched off from Ni foam substrate.

4 Fig. 2 (a-b) display the SEM images of as-deposited NiO and NiOG films. It shows that both NiO
5 and NiOG films have similar reticular-like porous structures with average pore diameter at about 5 μm
6 and average pore wall thickness at about 1 μm . The irregular shape of pores can be commonly
7 observed in ESD based materials where pores are the result from gradual decomposition of organic
8 precursors [18-21, 24, 25]. The magnified images (insets in Fig. 2) reveal that small quantity of
9 nanoparticles with various sizes on the pore walls of the NiOG sample could also be found. The sizes
10 of small particles could be the un-dispersed graphene nanoplates. The highly interconnected pores
11 could increase the contact area between active materials and electrolyte, buffer the volume change and
12 enhance the kinetics during cycling [25].

13

1 Figure 2. SEM images of as-deposited (a) NiO and (b) NiOG electrodes; disassembled and washed (c)
2 NiO and (d) NiOG electrodes after 610 cycle charge-discharge test.

3 To investigate the electrochemical performance of as prepared electrodes, cyclic voltammetry (CV)
4 was measured at a scan rate of 0.2 mV s^{-1} in the voltage range from 0.02 to 3 V for the first 10 cycles,
5 as shown in Fig. 3. In the first cathodic cycle of the NiO electrode, there are two major reduction peaks
6 at 0.98 and 0.48 V, corresponding to initial reduction of NiO to Ni through a conversion reaction and
7 formation of a solid electrolyte interface (SEI) layer, respectively [26-28]. Two major peaks at 1.56
8 and 2.21 V can be observed in the following anodic cycle, corresponding to the decomposition of SEI
9 layers and oxidation of Ni to NiO [26-28]. In the second cycle, the cathodic peaks shift to around 1.43
10 and 0.55 V, while the anodic peaks shift slightly to around 1.64 and 2.45 V, respectively. The voltage
11 shift of the cathodic peaks between the first and the second cycle is partially caused by the lithium-ion
12 driven structural modification [29]. After the second cycle, the corresponding two major cathodic
13 peaks of NiO due to reduction and SEI formation shift slightly to lower (1.15 V) and higher (0.79 V)
14 voltages, respectively. While in the anodic branch, the Ni oxidation peak shift to 2.21 V and SEI
15 decomposition peak remains almost at the same voltage. For the NiOG electrode in Fig. 3b, unlike NiO
16 electrode, the first NiO reduction process only show a broad shoulder at around 0.85 V which merged
17 with SEI formation peak at 0.27 V. The different cathodic behavior may related to the addition of high
18 surface area graphene and improved electronic conductivity of the NiOG electrode [13, 30]. The SEI
19 decomposition peak owns similar shape and peak position as that of NiO the electrode. However, the
20 Ni oxidation peak at around 1.61 V became broader and shifted towards higher voltage compared to
21 the oxidation peaks of the NiO electrode. Nevertheless, the CV curves from both NiO and NiOG
22 electrodes share a common phenomenon that the SEI decomposition peaks are still obvious in the
23 following cycles which indicates that SEI formation/decomposition process contributes unneglectable
24 charge storage in both electrodes [8, 31].

Figure 3. The CV curves for the first ten cycles: (a) NiO and (b) NiOG electrodes at a scan rate of 0.2 mV s^{-1} between 0.02 and 3.0 V (vs. Li/Li⁺).

To test the rate capability and cycle life of both electrodes, charge-discharge measurements under various current densities ranging from 0.1 to 5 A g^{-1} were carried out and followed by cyclability test for 500 cycles at 0.5 A g^{-1} , as shown in Fig. 4 (a). The major trend for the rate capability test in the first 110 cycles is that as the current density increases, the specific discharge capacity decreases for both NiO and NiOG electrodes. After that, both cells experience gradual capacity increase and stabilization at current density of 0.5 A g^{-1} . For NiOG, the discharge capacities are 759, 774, 614, 447, 243 and 104 mAh g^{-1} at 0.1, 0.2, 0.5, 1, 2, and 5 A g^{-1} , respectively. Notably, even after cycling at extremely high current density of 5 A g^{-1} , the specific discharge capacity can gradually recovery to the initial value (614 mAh g^{-1} , 50th cycle, 0.5 A g^{-1}) when the current density is set back to 0.5 A g^{-1} after 500 cycles. For NiO, it shows relatively lower specific discharge capacities which are 573, 542, 428, 277, 141, and 54 mAh g^{-1} at 0.1, 0.2, 0.5, 1, 2, and 5 A g^{-1} , respectively. The recovered specific discharge capacity of NiO is 476 mAh g^{-1} at the 610th cycle after rate capability test. The first discharge/charge capacities are 1112/631 and $1544/840 \text{ mAh g}^{-1}$, resulting in a coulombic efficiency of 57% and 54% for NiO and NiOG, respectively. Then the coulombic efficiency rapidly increases to about 98% at the second cycles and remains nearly 100% thereafter for both samples. The capacity loss in the first cycle could be attributed to the SEI layer formation at potentials below 0.75 V. Higher irreversible capacity at the first charge-discharge cycle for the NiOG than the NiO is probably due to the higher surface area of NiOG with more side reactions from graphene. Future effort is required to

1 improve the Columbic efficiency of NiOG composite electrode to make it more suitable for the LIBs.
2 Furthermore, there are several issues of NiOG electrode worth highlighting here. Firstly, the discharge
3 capacities are higher than the theoretical capacity of NiO when discharged at low current densities of
4 0.1 and 0.2 A g⁻¹. Secondly, the specific discharge capacity of 104 mAh g⁻¹ was achieved when tested
5 at 5 A g⁻¹, corresponding to a discharge time of 75 s. As expected, the addition of graphene to make
6 composite electrodes manifest high rate capability and long term cycling stability compared to bare
7 NiO electrode. The enhanced performance is probably due to the increased electron conductivity by
8 graphene and decreased diffusion path for both electrons and ions. Due to the low electronic
9 conductivity nature of NiO, the charge-discharge performance at higher current densities could be
10 greatly affected leading to reduced amount of active NiO involved in the electrochemical reaction. The
11 addition of graphene provides extra electron conductive path and better kinetics, which could also
12 make more active materials involved in the reaction at higher current densities. The conductivity
13 enhancement from graphene has also been demonstrated from the EIS results in Fig. 5. In addition, the
14 test cells after 610 charge-discharge cycling were disassembled. The SEM images shown in Fig. 2(c-d)
15 indicate that the porous structure was preserved after cycling for both electrodes which from another
16 side explains the stable performance and long cycle lives of the NiO and NiOG electrodes.

17 We further evaluated the cycling performance of both NiO and NiOG electrodes under constant
18 current density of 1 A g⁻¹, as shown in Fig. 4(b). The NiO electrode shows stable specific discharge
19 capacity of ~140 mAh g⁻¹ from 20th cycle to 400th cycle, which is much lower than what has been
20 observed in rate capability test (277 mAh g⁻¹) under same current density. For NiOG electrode, it
21 exhibits similar trend as for NiO electrode before 120th cycle. A steady capacity increase up to 435
22 mAh g⁻¹ from 120th cycle to 360th cycle, and a slight capacity decrease to 400 mAh g⁻¹ in the following
23 40 cycles can be observed. It indicates that different test protocols could affect the cell electrochemical
24 performance in some extent. Future more detailed work needs to be done regarding this issue.

Figure 4. (a) Rate capability and cyclability curves for both NiO and NiOG under various current densities from 0.1 to 5 A g⁻¹ at the voltage window between 0.02 and 3.0 V (vs. Li/Li⁺); (b) cyclability test for both NiO and NiOG electrodes under constant current density of 1 A g⁻¹ for 400 cycles at the voltage window between 0.02 and 3.0 V (vs. Li/Li⁺).

In order to further analyze the charge-discharge performance, the representative charge and discharge voltage profiles in the first 10 cycles under 0.1 mA g⁻¹ were plotted in Fig. 5 (a-b). Both NiO and NiOG electrodes exhibit similar charge and discharge curves. In the first cycle of NiO electrode, it shows a potential plateau at around 1.25 V with an extended slope. After the first cycle, the long potential plateau is replaced by a sloping curve ranging from 1.75 to 0.75 V, which is in agreement with CV result shown in Fig. 3 (a) with slight mismatch of voltage values due to the different test approach. There is a large irreversible capacity in the first two cycles but it is dramatically reduced in the following cycles. The discharge curves from 5th cycle to 10th cycle exhibit negligible changes which indicates more stabilized reaction processes. For the NiOG electrode, compared to NiO, higher capacities were observed at corresponding same charge-discharge circles. At the 10th cycle, the discharge capacity is as high as 759 mAh g⁻¹, which is even higher than theoretical capacity of NiO

1 (718 mAh g⁻¹). One of the possible reason for the extra capacity could be the formation/decomposition
 2 of a gel-like polymeric film during cycling [8, 31, 32]. According to Su's research, the Ni
 3 nanoparticles may have electrochemical catalysis effect on such reversible reaction [31]. The charge-
 4 discharge voltage profiles at different cycles for both NiO and NiOG electrodes tested under same
 5 current density of 1 A g⁻¹ have also been plotted in Fig. 5 (c-d). For NiO electrode, the first two cycles
 6 shows some curvatures. But the charge-discharge curves change to almost straight lines for 100th and
 7 400th cycles. The discharge capacity decrease is almost come from <0.5 V part. However, for NiOG
 8 electrode, the capacity increased in the same region from 100th cycle to 400th cycle. As mentioned
 9 above that the reaction associates to <0.5 V region is the formation of gel-like polymeric film. So the
 10 enhanced capacity of NiOG electrode is partially from the reversible reaction of such gel-like
 11 polymeric film. However, the detailed study of the capacity contribution of such effect has not been
 12 done yet due to the complex electrochemical process. Future effort is required in order to quantify the
 13 capacity contribution from gel-like polymeric film.

14
 15 Figure 5. The discharge/charge profiles for the 1st, 2nd and 5th cycle for (a) NiO and (b) NiOG
 16 electrodes at the current density of 0.1 A g⁻¹; the discharge/charge profiles for the 1st, 2nd 100th and
 17 400th cycle for (c) NiO and (d) NiOG electrodes at the current density of 1 A g⁻¹.

Figure 6. Nyquist plots of NiO and NiOG based half cells (figure inset: enlargement of Nyquist plots at high frequencies and the equivalent circuit used for fitting the experimental data. Dash lines represents fitting data).

Table 1. Summary of EIS fitting data for NiO and NiOG based half cells.

	NiO	NiOG
R_1 (Ohm)	10.4	7.2
R_2 (Ohm)	76.1	36.2
R_3 (Ohm)	66.3	12.1
s_2 (Ohm·s ^{-1/2})	146.2	51.1
C_3 (F)	9.3e-3	0.12

Electrochemical impedance spectroscopy (EIS) was conducted to verify and compare the electrode kinetics of the two electrodes. Fig. 6 shows the Nyquist plots for the two fresh cells made of NiO and NiOG separately. The experimental data are shown as symbols, and the dash line represents the fitted data according to the equivalent circuit shown in the inset in Fig. 6. The Nyquist plots for both electrodes are similar in shape, which comprise a depressed semicircle in the high frequency region, followed by a relative straight line at the low frequencies region. The semicircle in the high-frequency range is usually associated with the surface properties of the electrode, and the diameter of the semicircle corresponds to the charge-transfer resistance of the electrode [33, 34]. Obviously the diameter of the semicircle for NiO is larger compared with NiOG which indicates higher charge transfer resistance of NiO. In addition, the low frequency slope angle is ca. 71.2° for NiOG, which is

higher than that of NiO (ca. 64.9°). The steeper low-frequency tail (more close to vertical) indicates higher lithium ion conductivity in the electrode materials [33, 34]. Due to the single semicircle observed, the impedance can be ascribed to the combination of the surface film and charge-transfer resistance. The experimental data was fitted by the equivalent circuit (inserts of Fig. 6), in which R_1 represents the contact resistance, R_2 represents charge transfer resistance, R_3 represents solid electrolyte resistance, W_2 represents Warburg impedance related to Li^+ diffusion in the solution phase and constant phase element (CPE) represents the behavior of a double layer. According to the fitting, the value of R_1 is $\sim 10\ \Omega$ and $\sim 7\ \Omega$ for NiO and NiOG, respectively. The fitting data for R_2 ($\sim 36\ \Omega$) from NiOG is much lower than that of NiO ($\sim 76\ \Omega$), which means that the NiOG electrode has a faster charge transfer process than NiO. The R_3 value for NiO is $\sim 66\ \Omega$, which is also larger than what has been obtained for NiOG ($\sim 12\ \Omega$). The detailed EIS fitting data are shown in Table 1. As expected, the NiOG composite electrode possesses a high electrical conductivity, a rapid charge-transfer process, and good Li-ion kinetics for lithium uptake and extraction. Therefore, the outstanding electrochemical performance of NiOG can be explained by interpolant EIS data.

This work demonstrates that porous NiOG composite thin film electrode exhibits high rate capability with good cycle performance, which could be attributed to ESD derived porous structure and the addition of graphene in NiO. The porous structure can not only alleviate the volume change during cycling, but also shorten the ion diffusion length. The kinetic enhancement from graphene component enables the high rate performance. However, there are still some remaining issues need to be solve, including low 1st cycle Columbic efficiency and high polarization. We believe future great effort is needed to solve these remaining issues, such as developing advanced electrolyte to depress side reactions in the first cycle to improve columbic efficiency and introducing other catalytic effort to lower the polarization, etc. It could be noticed that the upper cutoff voltage is as high as 3.0 V for the NiO/graphene composite electrodes, indicating that the narrow voltage window when paring this electrode with other regular cathodes will result in low cell energy densities. Future work needs to be done to somewhat alleviated this issue by compositing with other low working voltage anode materials or pairing with higher voltage cathode materials in full cell to ensure an acceptable energy density.

4. Conclusions

In conclusion, porous NiOG composite electrodes have been prepared by ESD. Compared to NiO electrode, NiOG exhibits improved energy capacity and better rate capability. Due to the addition of graphene, as compared to pure NiO electrode, NiOG composite electrode exhibits enhanced rate capability (759, 774, 614, 447, 243 and 104 mAh g⁻¹ at 0.1, 0.2, 0.5, 1, 2, and 5 A g⁻¹, respectively) and excellent cycling performance (no capacity decrease for 500 cycles at 0.5 A g⁻¹). The EIS analysis confirms improved kinetics due to the addition of graphene in the composite. In addition, the porous structure generated from ESD process could alleviate the volume change during cycling and shorten the ion diffusion length, which enable long cycle life and high rate capability. CV results reveal that both conversion reaction of NiO and SEI formation/decomposition contribute to the major part of charge storage. This work demonstrates that the porous NiOG composite thin film is a promising electrode material for high performance LIBs.

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