

DELITHIATED COBALT OXIDE AND NICKEL OXIDE
PHASES AND METHOD OF PREPARING SAME

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BACKGROUND OF THE INVENTION

The increasing commercial importance of rechargeable lithium ion battery cells has prompted a desire to identify and to prepare cathode materials better able to reversibly intercalate and deintercalate lithium ions at greater voltages. There are three prominent reversible lithium intercalation compounds used for lithium ion rechargeable batteries: LiCoO_2 and LiNiO_2 compounds, as well as LiMn_2O_4 spinel.

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LiCoO_2 cells are of particular interest because of their ability to insert/deinsert lithium reversibly at voltages greater than 4V resulting in batteries that have an output voltage and an energy density 3 times greater than Ni-Cd. The theoretical charge capacity of LiCoO_2 cells is large at about 275 Amp-hours/kilogram (A-h/kg). In practical application, however, the maximum obtainable capacity for LiCoO_2 cells has been only about 140 A-h/kg, corresponding to a maximum charge voltage of about 4.2 V.

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Previous attempts to exceed this charge cutoff voltage in LiCoO_2 cells have caused poor cell performance manifested by severe loss of charge capacity in subsequent charge-discharge cycles. The commonly-held reason for the 4.2 volt charge limitation for LiCoO_2 cells was that electrochemical delithiation of LiCoO_2 above this voltage destabilized the

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structure of the partially delithiated LiCoO_2 phase, impairing intercalation of lithium in subsequent charge-discharge cycles.

Lithium cobalt oxide adopts a hexagonal structure consisting of CoO_2 layers separated by a Van der Waals gap. The octahedral sites within the Van der Waals gap are occupied by the Li^+ ions. This results in the reversible intercalation of lithium.

In such compounds, lithium acts as a glue or cement, screening the repulsive interactions between the negatively charged CoO_2 layers. When the compound is fully lithiated LiCoO_2 , the screening effect is greatest. As lithium is removed, the screening effect is decreased and the repulsions between the two CoO_2 layers are enhanced resulting in an expansion of the c-axis parameter. Due to the screening effect of lithium, it was believed that complete lithium deintercalation to form CoO_2 was not possible.

Ohzuku et al., *J. Electrochem. Soc.*, Vol. 141, No. 11, Nov. 1994, p. 2972, have succeeded in removing approximately 85% of the lithium. Their efforts revealed a monoclinic phase and questioned the existence of a CoO_2 phase.

In another theory, Reimers and Dahn, *J. Electrochem. Soc.*, 139, 2091, (1992), states that excess Co^{4+} destroys the crystallinity of the lithium cobalt oxide structure. Apparently, it inhibits the formation of highly crystalline phases at low lithium contents.

Wizansky, Rauch, and DiSalvo, *Journal of Solid State Chemistry*, 81, 203-207 (1989), investigated the delithiation of

LiCoO₂ through the use of powerful oxidizing agents such as NO₂⁺ and MoF₆. Their results showed that this approach merely decomposes the LiCoO₂.

5 LiNiO₂ is isostructural with LiCoO₂ and is commercially viable for use in secondary lithium ion batteries. Heretofore, no one has been capable of obtaining the delithiated NiO₂ phase. Ohzuku et al., J. Electrochem. Soc., Vol. 140, No. 7, July 1993, working with the nickel oxide reported Li_{0.98}NiO₂ and
10 approximated that this was the end phase.

 Lithium secondary batteries are generally recognized and are described for instance in U.S. Patent No. 5,296,318 to Gozdz et al., which is incorporated in its entirety herein by
15 reference. Lithium metal-free "rocking-chair" batteries may thus be viewed as comprising two lithium-ion-absorbing electrode "sponges" separated by a lithium-ion-conducting electrolyte, usually comprising a Li⁺ salt dissolved in a non-aqueous solvent or mixture of such solvents. Numerous such
20 salts and solvents are known in the arts, as evidence in Canadian Patent Publication No. 2,022,191, dated 30 January 1991.

 When cells comprising these previously-available
25 electrolytes are cycled to a voltage even slightly greater than 4.3 V, electrolyte oxidation occurs. Although small, this oxidation can jeopardize the capacity, cycle life, and safety of the battery cell. For example, the electrode oxidation reaction consumes part of the charging current, which cannot be
30 recovered when discharging the cell. The result is a continuous loss in the cell capacity over subsequent cycles. Further, if

during each charge a small part of the electrolyte is consumed, excess electrolyte must be included when the cell is assembled. The excess electrolyte reduces the amount of active material for a constant volume battery body, thereby decreasing initial capacity. In addition, the oxidation of the electrolyte often generates solid and gaseous by-products. The solid by-products build up a passivating layer on the particles of the active material, essentially increasing the polarization of the cell and lowering the output voltage. Simultaneously, and more importantly, the gaseous by-products increase the internal pressure of the cell, thereby increasing the risk of explosion and leading to unsafe and unacceptable operating conditions.

U.S. Patent No. 5,192,629, which is herein incorporated by reference in its entirety, provides a class of electrolyte compositions that are exceptionally useful for minimizing electrolyte decomposition in secondary batteries comprising strongly oxidizing positive electrode materials. These electrolytes are thus uniquely capable of enhancing the cycle life and improving the temperature performance of practical "rocking chair" cells. These electrolyte compositions have a range of effective stability extending up to about 5.0 V at 55°C, as well as at room temperature (about 25°C).

Electrolytes that are substantially inert to oxidation include a 0.5M to 2M solution of LiPF_6 , or LiPF_6 with up to about an equal amount of LiBF_4 added, in a mixture of dimethylcarbonate (DMC) and ethylene carbonate (EC) within the weight percent ratio range from about 95 DMC:5 EC to 20 DMC:80 EC. In a preferred electrolyte solution, the solvent ratio range is about 80 DMC:20 EC to 20 DMC:80 EC. An optimum

composition for operation at room temperature and below is an approximately 1.5M LiPF₆ solution in a solvent mixture of about 67 DMC:33 EC. A battery operating at room temperature and higher, e.g., in the range of 55°C, optimally utilizes an electrolyte consisting essentially of an approximately 1.5M LiPF₆ solution in a solvent combination of about 33 DMC:67 EC. An additionally useful electrolyte consists essentially of an approximately 1M to 2M solution of equal parts of LiPF₆ and LiBF₄ in a solvent mixture of about 50 DMC:50 EC.

Negligible current increases, after the reversible Li intercalations, at voltages up to about 5 V vs. Li indicates this remarkable stability that enables enhanced cell capacity not only in the "rocking chair" cells comprising negative electrodes of carbon, e.g., petroleum coke, but also in Li negative electrode cells. Such a lithium metal cell utilizing a LiCoO₂ positive electrode may be reasonably expected to achieve normal operating ranges of about 4.3 to 5.1 V.

With the aid of electrolytes which are substantially inert to oxidation and solid state electrolytic cells, fully delithiated phases of both CoO₂ and NiO, were obtained.

SUMMARY OF THE INVENTION

Accordingly, the present invention is directed to metastable CoO₂ and NiO₂ phases and their use as intercalation compounds for use in lithium ion secondary batteries. Features and advantages of this invention are set forth in the

description that follows, and they will be apparent from that description or can be learned by practice of the invention.

In one aspect, this invention relates to an
5 electrochemical method for preparing a stable cobalt dioxide
phase that includes preparing an electrolytic cell having an
anode, an electrolyte substantially inert to oxidation, and a
cathode including a lithium cobalt oxide intercalation complex;
and applying a voltage to the cell sufficient to completely
10 deintercalate lithium from the lithium cobalt oxide
intercalation complex, thereby forming a stable cobalt dioxide
phase in the cathode.

In a further aspect, this invention relates to a stable
15 cobalt dioxide phase prepared by the foregoing method.

In a further aspect, this invention relates to a stable
cobalt dioxide phase having the x-ray diffraction pattern:

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	$d(\text{\AA})$
	4.30 ± 0.02
	2.44 ± 0.02
	2.12 ± 0.02
	1.61 ± 0.02
25	1.41 ± 0.02
	1.34 ± 0.02
	1.17 ± 0.02

30 In a further aspect, this invention relates to an
electrochemical method for preparing a stable nickel dioxide

phase that includes providing a lithium nickel oxide intercalation complex having the formula Li_xNiO_2 , wherein x is preferably 0.8 to 1.0, preparing an electrolytic cell having a cathode including the lithium nickel oxide intercalation complex, and applying a voltage to the cell sufficient to delithiate completely the lithium nickel oxide intercalation complex.

In a further aspect, this invention relates to a stable nickel dioxide phase prepared by the above described process. In a further aspect, this invention relates to a stable nickel dioxide phase having the x-ray diffraction pattern:

	$d(\text{\AA})$
15	4.47 ± 0.02
	2.40 ± 0.02
	2.29 ± 0.02
	1.97 ± 0.02
	1.51 ± 0.02
20	1.41 ± 0.02
	1.38 ± 0.02

In a further aspect, the invention relates to the a method of making a secondary electrolytic cell including the stable CoO_2 or NiO_2 phase and the cell formed thereby.

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and with the description serve to explain the invention and its objects, advantages, and principles.

BRIEF DESCRIPTION OF THE DRAWING

The present invention will be described with reference to
5 the accompanying drawing of which:

FIG. 1 is a series of x-ray diffraction diagrams taken
during electrochemical delithiation of LiCoO_2 to form the CoO_2
phase;
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FIG. 2 is a series of x-ray diffraction diagrams taken
during electrochemical intercalation of lithium into the CoO_2
phase;

15 FIG. 3 plots charge and discharge voltage versus lithium
content for a cell utilizing the CoO_2 phase;

FIGs. 4 and 5 plot charge and discharge voltage versus
lithium content for a cell having a LiNiO_2 cathode that has been
20 delithiated to the NiO_2 phase according to the invention;

FIG. 6 plots decomposition reaction heat versus
temperature for the CoO_2 and NiO_2 phase;

25 FIGs. 7 and 8 are x-ray diffraction diagrams for the
thermal decomposition products of the CoO_2 and NiO_2 phases;

FIG. 9 plots charge and discharge voltages versus sodium
content for a cell using the CoO_2 phase of this invention
30 intercalated with sodium ions;

FIG. 10 is an x-ray diffraction diagram taken during electrochemical delithiation of LiNiO_2 to form the NiO_2 phase; and

5 FIG. 11 is an x-ray diffraction diagram illustrating the effect of atmospheric water on the CoO_2 phase.

DESCRIPTION OF THE INVENTION

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One hindrance to the achievement of the CoO_2 and NiO_2 phases of the present invention, was removed by the development of electrolytes that are stable (inert to oxidation) at the high
15 voltages thought necessary to achieve the delithiated CoO_2 phase. These electrolytes are exemplified by those described in U.S. Patent No. 5,192,629, the disclosure of which is incorporated herein by reference. Nonetheless, it was commonly held that the CoO_2 phase was unattainable because in the
20 complete absence of lithium ions in the Van der Waals gap between the negatively-charged CoO_2 layers, the repulsive force between the layers would be too great and a completely delithiated CoO_2 phase would never be stable.

25 Using an electrolytic cell incorporating an LiCoO_2 cathode material described herein and a high voltage-stable electrolyte, the CoO_2 phase can be prepared by applying to the cell a charge voltage of 5.2 V, which will deintercalate substantially all the lithium from the LiCoO_2 cathode, forming
30 the CoO_2 phase. The CoO_2 phase is metastable and decomposes above 200°C.

Similarly, in an electrolytic cell using a high voltage-stable electrolyte and a LiNiO_2 cathode, a substantially complete delithiation to a NiO_2 phase can be achieved by applying a charge voltage of 5.1 V.

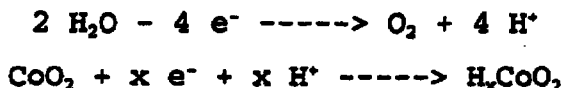
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Once obtained, the CoO_2 and NiO_2 phases of the present invention can be reintercalated with lithium, or by other ions such as hydrogen nuclei, sodium (Example 4), potassium, or rubidium. Reintercalation of lithium or other ionic species into the CoO_2 or NiO_2 phases can be accomplished by electrochemical insertion or by vapor phase transport at temperatures below 200°C . Vapor phase transport is described in a paper by Tarascon et al., "Synthesis and peculiar properties of $\text{InMo}_6\text{S}_{x-3}\text{Se}_x$, $\text{TlMo}_6\text{S}_{x-3}\text{Se}_x$ and $\text{Hg}_2\text{Mo}_6\text{S}_{x-3}\text{Se}_x$ ", *Physical Review B*, Vol. 31, NO. 2, 1985, which is incorporated herein by reference in its entirety.

Following reintercalation, these phases can, for example, be cycled with lithium between 3 V and 4.2 V for the CoO_2 phase and 2.8 V and 4.1 V for the NiO_2 phase without loss of cell capacity.

After formation of the CoO_2 phase, CoOOH may be formed by exposure of the phase to atmospheric water. As can be seen from FIG. 11, CoO_2 may be formed in situ in an electrochemical cell. After exposure to air for approximately 30 minutes, two phases are present. After 3 days in air CoOOH was formed, because at an open circuit voltage >4 V the following reaction occurs:

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The CoOOH may be used as an electronic conductor in other battery technology. This includes application in the Ni electrode or NiMeH, Ni-H or Ni-Cd batteries in which cobalt is already used.

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As an alternative, once formed, these phases can be used in any variety of manners. In one preferred embodiment, the cathode of a plastic solid state cell is not laminated to the underlying electrolyte/anode structure, thus allowing ease of removal of the CoO₂ or NiO₂ phase in a plastic matrix. This plasticized phase can then easily be transported to other environments. For the reasons discussed above, if the pure CoO₂ phase is desired, handling under inert (anhydrous) conditions is preferred.

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In another embodiment, this plasticized phase is placed into a cell containing, for example, a sodium containing electrolyte and a compatible electrolyte and then the cobalt or nickel oxide phase is reintercalated with the sodium ions. This reintercalation may be stopped short of completion and, in that way, a second or subsequent ion may be added to the reintercalated metal oxide phase.

In yet another embodiment, the nickel or cobalt oxide phase may be combined with an organic component to form, for example, either a composite polymer or an activated metal oxide carrier. The redox potential of this phase is high making it potentially useful in many areas. Anticipated applications include, for example, forming inorganic polymer structures and as a biochemical carrier. Such applications would be clearly recognizable to the skilled artisan.

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The following examples exemplify the practice of the present invention to the prior art. It will be appreciated by those skilled in the art that these examples are not to be construed as limiting the present invention.

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Example 1

A plastic electrolytic cell was constructed comprising a matrix of polyvinylidene fluoride (PVdF) and hexafluoro-propylene (HFP), incorporating an electrolyte composition of 10 2 parts EC to one part DMC and 1M LiPF_6 , which was inert to oxidation at high voltages. The cathode contained LiCoO_2 as an active material and the anode contained carbon. The anode and the solid state electrolyte were laminated to one another and 15 the cathode was placed thereover.

This cell was charged to 5.2 V, at which point the LiCoO_2 was fully delithiate to form the CoO_2 phase. The existence of this phase is confirmed by the x-ray data depicted in FIG. 1. 20 FIG. 1 depicts the diffraction pattern at the end of deintercalation of LiCoO_2 , beginning at approximately the last known phase disclosed in the prior literature, i.e., monoclinic ($\text{Li}_{0.15}\text{CoO}_2$) and proceeding to complete delithiation at a voltage of 5.2V.

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The x-ray diffraction patterns were obtained in-situ through the use of an X-ray diffraction apparatus that allows the use of high voltages without corrosion of the beryllium window.

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The final x-ray diffraction pattern obtained at 5.2 V is the hexagonal structure associated with the CoO_2 phase.

Moreover, once obtained, the CoO_2 phase reconverted to the LiCoO_2 phase during discharge of the cell as shown by the series of x-ray diffraction patterns in FIG. 2. Following attainment of the CoO_2 phase in the cathode and reintercalation of lithium to form the LiCoO_2 phase, this cell was cycled between 3 V and 4.2 V with little loss of charge capacity, as seen in FIG. 3.

During the charge cycle of a partially delithiated cobalt oxide, reinsertion of the lithium forms a monoclinic phase; however, reinsertion of lithium into the fully delithiated cobalt oxide resulted in a hexagonal structure, which is the same as the structure of the LiCoO_2 originally incorporated into the electrolytic cell.

Example 2

A plastic electrolytic cell was constructed as in Example 1, incorporating an electrolyte composition inert to oxidation at high voltages and a cathode made from LiNiO_2 . This cell was charged to 5.1 V, at which voltage substantially all of the lithium was removed from the LiNiO_2 phase to form the NiO_2 phase. The existence of the NiO_2 phase is confirmed by the x-ray data depicted in FIG. 10.

The cell was discharged at 200 μA , whereupon 70% of the lithium intercalated back into the NiO_2 structure, as seen in FIG. 4. Subsequent cycling this cell between 2.8 V and 4.0 V without capacity fading confirmed that the reversible charge characteristics of the Li_xNiO_2 were not destroyed by the attainment of the NiO_2 phase. Reducing the discharge current to 150 μA resulted in intercalation of all of the lithium to form

the LiNiO_2 phase. As shown in FIG. 5, subsequent cycling of this cell between 2.8 V and 4.1 V resulted in a high capacity (greater than 190 A-h/kg) with minimal polarization and slight irreversibility characteristic of LiNiO_2 . These results show that total removal of lithium from LiNiO_2 produces a structure that remains electrochemically active.

Example 3

A study of the thermal stability of the CoO_2 phase and NiO_2 phase was undertaken. Plastic electrodes of LiCoO_2 and LiNiO_2 brought to the CoO_2 phase and the NiO_2 phase in the manners described in Examples 1 and 2, respectively, were dissolved separately in a dilute acetone solvent at room temperature. The plastic portions of the electrodes dissolved in the solvent, and the insoluble metal oxides settled to the bottom of the vessels. The metal oxides were separated from the solution and analyzed using differential scanning calorimetry (DSC) ramped to 300°C at 10°C/min.

As seen in FIG. 6, a relatively strong exothermic reaction occurred at 200°C for both the CoO_2 and NiO_2 phases. Analysis of the samples by x-ray diffraction after DSC revealed that both phases reduced with attendant oxygen loss according to the reaction



The x-ray diffraction patterns depicted in FIGs. 7 and 8 confirm that the samples transformed into the mixed rocksalt structures of CoO and NiO , which are known to be electrochemically inactive to lithium intercalation.

Example 4

A cell was constructed as in Example 1. The CoO_2 phase was formed by delithiating the plastic cell at 5.2 V for 15 hours.

5 After the CoO_2 phase was formed, the plasticized CoO_2 was removed from the electrolyte/anode structure and then incorporated into a similarly constructed cell contained sodium.

10 The new cell was constructed using the plastic CoO_2 cathode, an NaClO_4 electrolyte and a sodium metal anode. Sodium was introduced into the CoO_2 phase by discharging the cell at 2.2 V to insert the sodium. The cell was then cycled between 2.2 V and 4.1 V, as shown in FIG. 9.

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What is claimed is:

1. A method of preparing a stable metal dioxide phase
5 characterized in that said method comprises:
 - a) preparing an electrolytic cell having an anode, an electrolyte inert to oxidation, and a cathode comprising a metal oxide selected from the group consisting of a lithium
10 cobalt oxide intercalation complex and a lithium nickel oxide intercalation complex having the formula Li_xNiO_2 , wherein x is 0.8 to 1.0; and
 - b) applying to said cell a voltage sufficiently high to deintercalate substantially all lithium from said metal oxide.
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2. A method according to claim 1 wherein said voltage is in excess of about 5.0 V.
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3. A method according to claim 2 wherein said electrolyte comprises a 0.5M to 2M solution of LiPF_6 , or LiPF_6 with up to about an equal amount of LiBF_4 added, in a mixture of dimethyl-
carbonate (DMC) and ethylene carbonate (EC) within the weight
25 percent ratio range from about 95 DMC:5 EC to 20 DMC:80 EC.
4. A method according to claim 1 which further comprises intercalating said stable metal dioxide phase with an element
30 selected from the group consisting of lithium, sodium, potassium, rubidium, and hydrogen.



5. A stable metal dioxide phase prepared according to the method of claim 1

characterized in that
the metal is selected from the group consisting of cobalt and
5 nickel.

6. A stable cobalt dioxide phase according to claim 5 having the X-ray diffraction pattern:

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d(Å)
4.30 ± 0.02
2.44 ± 0.02
2.12 ± 0.02
15 1.61 ± 0.02
1.41 ± 0.02
1.34 ± 0.02
1.17 ± 0.02

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7. A stable nickel dioxide phase according to claim 5 having the X-ray diffraction pattern:

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d(Å)
4.47 ± 0.02
2.40 ± 0.02
2.29 ± 0.02
1.97 ± 0.02
1.51 ± 0.02
30 1.41 ± 0.02
1.38 ± 0.02



8. A secondary electrolytic cell including an anode, an electrolyte, and a cathode

characterized in that
said cathode comprises a stable metal dioxide phase of claim 5.

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9. A secondary electrolytic cell according to claim 8

characterized in that
said cathode further comprises an element selected from the
group consisting of lithium, sodium, potassium, rubidium, or
hydrogen intercalated into said stable metal dioxide phase.

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