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CA 2859121 A1 2013/05/23

(21) 2 859 121

(12) DEMANDE DE BREVET CANADIEN CANADIAN PATENT APPLICATION

(13) A1

(86) Date de dépôt PCT/PCT Filing Date: 2012/11/14
(87) Date publication PCT/PCT Publication Date: 2013/05/23
(85) Entrée phase nationale/National Entry: 2014/06/12
(86) N° demande PCT/PCT Application No.: JP 2012/079484
(87) N° publication PCT/PCT Publication No.: 2013/073562
(30) Priorité/Priority: 2011/11/15 (JP2011-250184)

(51) Cl.Int./Int.Cl. *C01B 25/45* (2006.01), *C01B 31/02* (2006.01), *H01M 4/136* (2010.01), *H01M 4/36* (2006.01), *H01M 4/58* (2010.01)

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(54) Titre : PARTICULES COMPOSITES, LEUR PROCEDE DE PRODUCTION, MATERIAU D'ELECTRODE POUR BATTERIES SECONDAIRES, ET BATTERIE SECONDAIRE

(54) Title: COMPOSITE PARTICLES, MANUFACTURING METHOD THEREOF, ELECTRODE MATERIAL FOR SECONDARY BATTERY, AND SECONDARY BATTERY

(57) Abrégé/Abstract:

Provided is a positive electrode material for lithium ion secondary batteries that are highly safe and can be charged and discharged with a large current, while having long service lives. Composite particles, each of which is obtained by coating a lithium-containing phosphate particle with a carbon film that contains one or more carbon materials selected from the group consisting of (i) fibrous carbon materials, (ii) chain-like carbon materials and (iii) carbon materials that are obtained by connecting a fibrous carbon material and a chain-like carbon material with each other. It is preferable that each fibrous carbon material is a carbon nanotube having an average fiber diameter of 5-200 nm. It is preferable that each chain-like carbon material is carbon black wherein primary particles having an average particle diameter of 10-100 nm are bonded together in a chain form. It is preferable that the lithium-containing phosphate is $LiFePO_4$, $LiMnPO_4$, $LiMnXFe_{(1-X)}PO_4$, $LiCoPO_4$ or $Li_3V_2(PO_4)_3$.

(12) 特許協力条約に基づいて公開された国際出願

(19) 世界知的所有権機関
国際事務局

(43) 国際公開日
2013 年 5 月 23 日(23.05.2013)

WIPO | PCT

(10) 国際公開番号
WO 2013/073562 A1

(51) 国際特許分類:
C01B 25/45 (2006.01) *H01M 4/36* (2006.01)
C01B 31/02 (2006.01) *H01M 4/58* (2010.01)
H01M 4/136 (2010.01)

(21) 国際出願番号: PCT/JP2012/079484

(22) 国際出願日: 2012 年 11 月 14 日(14.11.2012)

(25) 国際出願の言語: 日本語

(26) 国際公開の言語: 日本語

(30) 優先権データ:
特願 2011-250184 2011 年 11 月 15 日(15.11.2011) JP

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(81) 指定国 (表示のない限り、全ての種類の国内保護が可能): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) 指定国 (表示のない限り、全ての種類の広域保護が可能): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), ユーラシア (AM, AZ, BY, KG, KZ, RU, TJ, TM), ヨーロッパ (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

添付公開書類:

— 国際調査報告（条約第 21 条(3)）

(54) **Title**: COMPOSITE PARTICLES, METHOD FOR PRODUCING SAME, ELECTRODE MATERIAL FOR SECONDARY BATTERIES, AND SECONDARY BATTERY

(54) 発明の名称 : 複合粒子、その製造方法、二次電池用電極材料及び二次電池

(57) **Abstract**: Provided is a positive electrode material for lithium ion secondary batteries that are highly safe and can be charged and discharged with a large current, while having long service lives. Composite particles, each of which is obtained by coating a lithium-containing phosphate particle with a carbon film that contains one or more carbon materials selected from the group consisting of (i) fibrous carbon materials, (ii) chain-like carbon materials and (iii) carbon materials that are obtained by connecting a fibrous carbon material and a chain-like carbon material with each other. It is preferable that each fibrous carbon material is a carbon nanotube having an average fiber diameter of 5-200 nm. It is preferable that each chain-like carbon material is carbon black wherein primary particles having an average particle diameter of 10-100 nm are bonded together in a chain form. It is preferable that the lithium-containing phosphate is $LiFePO_4$, $LiMnPO_4$, $LiMn_XFe_{(1-X)}PO_4$, $LiCoPO_4$ or $Li_3V_2(PO_4)_3$.

(57) 要約: 安全性が高く、大電流充放電が可能で、しかも長寿命なリチウムイオン二次電池用正極材を提供する。 リチウム含有リン酸塩粒子が、（i）繊維状炭素材料、(ii)鎖状炭素材料、および（iii）繊維状炭素材料と鎖状炭素材料とが相互に連結してなる炭素材料からなる群より選ばれた１種以上の炭素材料を含有する炭素膜で被覆されてなる複合粒子。繊維状炭素材料が、平均繊維径が５～２００ｎｍのカーボンナノチューブであることが好ましい。鎖状炭素材料が、平均粒径１０～１００ｎｍの一次粒子が鎖状に結合してなるカーボンブラックであることが好ましい。リチウム含有リン酸塩が、$LiFePO_4$、$LiMnPO_4$、$LiMn_xFe_{(1-x)}PO_4$、$LiCoPO_4$又は$Li_3V_2(PO_4)_3$であることが好ましい。

WO 2013/073562 A1

DESCRIPTION

COMPOSITE PARTICLES, MANUFACTURING METHOD THEREOF, ELECTRODE MATERIAL FOR SECONDARY BATTERY, AND SECONDARY BATTERY

Technical Field

The present invention relates to electrode materials for a lithium-ion secondary battery.

Background Art

In a lithium-ion secondary battery, a negative electrode may be formed using material capable of storing and releasing a lithium ion. The lithium-ion secondary battery may have less precipitation of dendrites than a lithium secondary battery having a negative electrode made of metal lithium. Because of this, the lithium-ion secondary battery has advantages that a high-capacity battery with an increased energy density can be provided while a short circuit in the battery is prevented to increase its safety.

Recently, a much higher capacity of this lithium-ion secondary battery has been sought. At the same time, it is required for a cell for high-power usage that cell resistance is reduced to increase performance of charging and discharging a large current. In this respect, the following considerations have been conventionally given: to increase a capacity of carbon-based negative electrode material and/or positive electrode material made of lithium metal oxide, a cell reactant; to miniaturize reactant particles; to increase an electrode surface area by increasing a specific surface area of the particles and/or by designing a cell; and to reduce liquid diffusion resistance by making a separator thinner, etc. However, in one hand, the particles are made smaller and the specific surface area is increased, which causes an increase in an amount of a binder. On the other hand, this increase is inconsistent with making the capacity higher. Further, positive and negative electrode materials are peeled and detached from a metal foil, which is a collector. This results in a short circuit inside a cell. Consequently, cell voltage is lowered and uncontrolled heating occurs, etc., so that the lithium-ion secondary battery sometimes becomes unsafe. Then, consideration has been made to modify a type of the binder so as to increase adhesion to the foil (see Patent Literature 1).

However, the modification of the type of the binder may increase the cell capacity, but insufficiently improves characteristics of charging and discharging a large current by decreasing its resistance. When the lithium-ion secondary batteries are compared with secondary batteries such as a nickel-cadmium battery and a nickel-hydrogen battery, it is difficult to develop application to an electric tool and a hybrid car. This is because in the application, a large current should be charged and discharged in a long period of time, which provides a big performance barrier for the lithium-ion secondary batteries.

In view of charging and discharging a large current in the lithium-ion secondary battery, a carbon conductive material has been devised so as to decrease its electrode resistance (see Patent Literatures 2 to 4). Unfortunately, when a large current is used to repeat a cycle of charge and discharge, positive and negative electrode materials are subject to expansion and contraction, which damages a conductive path of particles between positive and negative electrodes. As a result, a large current cannot be made to flow after a short period of time.

Meanwhile, metal oxide such as $LiCoO_2$, $LiNiO_2$, Li_2MnO_4, or $LiCo_xNi_yMn_zO_2$ $(x + y + z = 1)$ has been conventionally used as a positive electrode active substance for the lithium-ion secondary battery. Recently, much attention has been paid to lithium-containing phosphate such as $LiFePO_4$, $LiMnPO_4$, $LiMn_xFe_{(1-x)}PO_4$, $LiCoPO_4$, or $Li_3V_2(PO_4)_3$.

The first feature of the lithium-containing phosphate is that its anion is a polyanion (a phosphate ion: PO_4^{3-}), which is more stable than an oxide ion (O^{2-}). Differing from metal oxide, the lithium-containing phosphate generates no oxygen (O_2), which is a combustion-supporting substance, after decomposition. Accordingly, use of the lithium-containing phosphate as a positive electrode active substance can increase safety of the lithium-ion secondary battery.

The second feature of the lithium-containing phosphate is that resistance of the material itself is large. Consequently, it is a big issue to make the battery highly conductive (see Patent Literatures 5 and 6). In order to provide possible solutions, various considerations have been made: to coat the surface of particles of the lithium-containing phosphate with carbon, a conductive material, to prepare positive electrode material; or to make a composite of the lithium-containing phosphate and carbon, etc., (see Patent Literatures 7 to 13). These considerations have improved performance of the positive electrode material using phosphate.

Citation List

Patent Literature

[0009]

Patent Literature 1: JP05-226004A
Patent Literature 2: JP2005-19399A
Patent Literature 3: JP2001-126733A
Patent Literature 4: JP2003-168429A
Patent Literature 5: JP2000-509193A
Patent Literature 6: JP09-134724A
Patent Literature 7: JP2002-75364A

Patent Literature 8: JP2002-110162A
Patent Literature 9: JP2004-63386A
Patent Literature 10: JP2005-123107A
Patent Literature 11: JP2006-302671A
Patent Literature 12: JP2007-80652A
Patent Literature 13: JP2010-108889A
Patent Literature 14: JP2009-503182A

SUMMARY OF INVENTION

Technical Problem

The above carbon coating of the positive electrode active substance may enhance electron conductivity. However, when contraction and expansion of the positive electrode active substance are repeated during cycles of charge and discharge, an electrical contact between the carbon coating and its surrounding conduction aid gradually deteriorates inside the positive electrode material. This likely causes a voltage drop and capacity reduction of a cell during a long period of the cycles. Accordingly, the above carbon coating has not radically improved the long-term cycle characteristics. Also, the above problems have not been resolved by a conventional technology in which lithium-containing phosphate and carbon are used to form a composite.

The present invention has been made to address the foregoing issues on positive electrode material for a lithium-ion secondary battery. It is an object of the present invention to provide positive electrode material for a lithium-ion secondary battery in which stable charge and discharge characteristics can be maintained over a long period of service life of the battery.

Solution to Problem

Specifically, in order to solve the above problems, the present invention has the following aspect (1):

(1) Composite particles comprising: particles of lithium-containing phosphate; and carbon coating comprising at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material, wherein each particle is coated with the carbon coating.

In addition, the present invention preferably provides the following aspects:

(2) The composite particles according to the aspect (1), wherein the fibrous carbon material is a carbon nanotube with an average fiber size of 5 to 200 nm;

(3) The composite particles according to the aspect (1) or (2), wherein the chain-like carbon material is carbon black produced by linking, like a chain,

primary particles with an average particle size of 10 to 100 nm;

(4) The composite particles according to any one of the aspects (1) to (3), wherein the lithium-containing phosphate is $LiFePO_4$, $LiMnPO_4$, $LiMn_XFe_{(1-X)}PO_4$, $LiCoPO_4$, or $Li_3V_2(PO_4)_3$;

(5) The composite particles according to any one of the aspects (1) to (4), wherein primary particles have an average size of 0.02 to 20 μm;

(6) A process for producing the composite particles according to any one of the aspects (1) to (5), the process comprising: a first step of subjecting to surface treatment at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material; a second step of dispersing and mixing the at least one surface-treated carbon material in a solution having dissolved in a solvent a lithium ion (Li^+), a phosphate ion (PO_4^{3-}), and a metal ion other than from lithium, and a heat-degradable carbon source compound; a third step of heating the mixture as a solution state; and a fourth step of drying and further heating the mixture to form composite particles, wherein each particle of lithium-containing phosphate is coated with carbon coating comprising the at least one carbon material;

(7) A process for producing the composite particles according to any one of the aspects (1) to (5), the process comprising: a first step of subjecting to surface treatment at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material; a second step of heating a solution having dissolved in a solvent a lithium ion (Li^+), a phosphate ion (PO_4^{3-}), and a metal ion other than from lithium as a solution state to form particles of lithium-containing phosphate and/or particles of a precursor thereof; a third step of mixing the at least one surface-treated carbon material obtained in the first step, the particles obtained in the second step, and a heat-degradable carbon source compound; and a fourth step of heating the mixture to form composite particles, wherein each particle of lithium-containing phosphate is coated with carbon coating comprising the at least one carbon material;

(8) The process for producing composite particles according to the aspect (6) or (7), wherein the solvent is water, alcohol, or a mixed solvent of water and alcohol;

(9) The process for producing composite particles according to any one of the aspects (6) to (8), wherein a method using a pressured and heated solvent is used for the third step of the aspect (6) or the second step of the aspect (7);

(10) A process for producing the composite particles according to any one of the aspects (1) to (5), the process comprising: a first step of subjecting to surface treatment at least one carbon material selected from the group consisting of (i)

fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material; a second step of mixing the at least one surface-treated carbon material, particles of lithium-containing phosphate, and a heat-degradable carbon source compound; and a third step of heating the mixture to form composite particles, wherein each particle of lithium-containing phosphate is coated with carbon coating comprising the at least one carbon material;

(11) The process for producing composite particles according to any one of the aspects (6) to (10), wherein oxidation treatment is used for the surface treatment of the at least one carbon material;

(12) The process for producing composite particles according to any one of the aspects (6) to (10), wherein a method using a surfactant is used for the surface treatment of the at least one carbon material;

(13) The process for producing composite particles according to any one of the aspects (6) to (10), wherein a method using a polymer dispersant is used for the surface treatment of the at least one carbon material;

(14) Electrode material for a lithium-ion secondary battery, comprising 60 to 95% by mass of the composite particles according to any one of the aspects (1) to (5) and the remainder consisting of an conduction aid and a binder; and

(15) A lithium-ion secondary battery comprising: a positive electrode produced using the electrode material according to the aspect (14); a negative electrode; an electrolytic solution; and a separator that electrically insulates the positive electrode from the negative electrode and helps retain the electrolytic solution.

Advantageous Effects of Invention

In use of electrode material for a lithium-ion secondary battery according to the present invention, particles of a positive electrode active substance contain at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material. As the first effect, this carbon material can enhance an electron conduction network, so that electrons can be smoothly transferred between lithium-containing phosphate particles and a conduction aid. Further, the at least one carbon material is included in the carbon coating of the particles of lithium-containing phosphate of the positive electrode active substance. As the second effect, this inclusion helps retain an electric contact between the at least one carbon material and the positive electrode active substance. Consequently, repeating contraction and expansion of the positive electrode active substance during cycles of charge and discharge fails to deteriorate the contact. These two effects help enhance cycle characteristics of the battery and enable stable charge and discharge characteristics to be maintained over a long period of service life of the battery.

Description of Embodiments

The following details embodiments of the present invention.

In an embodiment of the present invention, composite particles comprise: particles of lithium-containing phosphate; and carbon coating comprising at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material, wherein each particle is coated with the carbon coating.

In an embodiment of the present invention, carbon material is (i) fibrous carbon material, (ii) chain-like carbon material, (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material, or a mixture thereof.

Examples of the fibrous carbon material include a carbon nanotube, carbon nanofiber, vapor-grown carbon fiber, polyacrylonitrile (PAN)-based carbon fiber, and pitch-based carbon fiber. Among them, a carbon nanotube with an average fiber size of 5 to 200 nm is preferable.

Examples of the chain-like carbon material include carbon black such as acetylene black (e.g., DENKA BLACK manufactured by DENKI KAGAKU KOGYO KABUSHIKI KAISHA) or furnace black (e.g., SUPER-P manufactured by TIMCAL GRAPHITE & CARBON, Inc.; Ketjenblack manufactured by Ketjen Black International Company). Among them, carbon black whose primary particles have an average size of 10 to 100 nm is preferable. Among the carbon black, particularly preferred is acetylene black.

Examples of a method for linking fibrous carbon material and chain-like carbon material include: but are not particularly limited to, a method for injecting fibrous carbon material during thermolysis of hydrocarbon to link the material and carbon black generated; a method for supplying and linking hydrocarbon containing a fibrous carbon-forming catalyst during thermolysis of acetylene gas and/or while acetylene gas is subjected to thermolysis (see Patent Literature 14); a method for dispersing fibrous carbon and carbon black into a liquid carbonization source such as hydrocarbon and alcohol to carbonize the liquid carbonization source by heating, etc., while keeping it in a liquid or gas phase; a method including: mixing beforehand a fibrous carbon-forming catalyst and carbon black; causing them to contact source gas for fibrous carbon; and linking the carbon black and the fibrous carbon while generating the fibrous carbon; and a method for linking fibrous carbon and carbon black by a mechanochemical process using a solid medium. Examples of the linking using a mechanochemical process include linking using a media mixing mill such as a bead mill, a vibrating mill, or a ball mill. For example, an SEM image can be examined to calculate an average fiber size of fibrous carbon material and an average particle size of primary particles of chain-like carbon material, which sizes may be a number average fiber size and a number average particle size, respectively. The average fiber size may be, for example, 5, 10, 15, 20, 30, 50, 100, 150, or 200 nm. The size may be between any two of the above values. The average particle size of primary particles of chain-like carbon material may be, for example, 10, 20, 30, 40, 50, 60, 70, 80, 90, or 100 nm. The size may be between any two of the above values.

In an embodiment of the present invention, lithium-containing phosphate may be phosphate capable of storing and releasing a lithium ion. Specific examples of the lithium-containing phosphate include $LiFePO_4$, $LiMnPO_4$, $LiMn_XFe_{(1-X)}PO_4$, $LiCoPO_4$, and $Li_3V_2(PO_4)_3$. Particularly preferred are $LiFePO_4$ and $LiMn_XFe_{(1-X)}PO_4$.

In an embodiment of the present invention, the composite particles have an average primary particle size of preferably 0.02 to 20 μm and more preferably 0.05 to 5 μm. When the particle size is smaller than the above, it is difficult to coat the lithium-containing phosphate with the carbon coating containing the above carbon material because the particles are too small. When the particle size is larger than that, the positive electrode material has a reduced number of the particles. Also, the positive electrode active substance and the conduction aid have a reduced number of their contacts. Accordingly, the advantageous effects of the present invention as described in paragraph (0011) cannot be sufficiently achieved. The average particle size may be, for example, 0.02, 0.05, 0.1, 0.5, 1, 2, 3, 4, 5, 10, 15, or 20 μm. The size may be between any two of the above values. This average particle size can be calculated by examining, for example, an SEM image and may be a number average particle size. In an embodiment of the present invention, the coating includes a state in which the entire surface of the coated particles is coated. This coating may be carried out using carbon coating to cover 90, 95, 98, 99, 99.5, 99.9, or 100% of the particle surface. This ratio may be between any two of the above values. The coating of the particles may be observed with an SEM.

Composite particles produced by coating particles of lithium-containing phosphate with carbon coating containing the above carbon material may be prepared by any of the following methods: (a) a method for mixing and heating the above surface-treated carbon material, source material for lithium-containing phosphate, and a heat-degradable carbon source compound; (b) a method for mixing and heating the above surface-treated carbon material, particles of lithium-containing phosphate as obtained by heating source material for the lithium-containing phosphate and/or particles of a precursor thereof, and a heat-degradable carbon source compound; and (c) a method for mixing and heating the above surface-treated carbon material, particles of lithium-containing phosphate, and a heat-degradable carbon source compound. Note that in the method (c), commercially available particles of lithium-containing phosphate (including carbon-coated particles) may be used.

The carbon material is subjected to surface treatment. This process is, for example, oxidation treatment or treatment using a surfactant or a polymer dispersant. Carbon material without surface treatment is unsuitable for the present invention because the material is unlikely to be incorporated in carbon coating during formation of the coating. In the oxidation treatment, an oxidizer is used on a surface of the above carbon material to introduce a hydroxyl group (-OH), a carbonyl group (>C=O), a carboxyl group (-COOH), or a functional group containing an ether bond or an ester bond. Specific examples of the oxidation treatment include: (i) heating the carbon material under an oxygen-containing atmosphere (gas phase oxidation); (ii) retaining the carbon material under an ozone-containing atmosphere or in an ozone-containing solution (ozone oxidation); (iii) heating the carbon material in a solution containing an oxidizing compound (e.g., sulfuric acid, nitric acid, perchloric acid, hydrogen peroxide, potassium permanganate, osmic acid); and(iv) subjecting the carbon material to treatment using a wet jet mill in water, an organic solvent containing a functional group such as a hydroxy group (-OH) or a carbonyl group (>C=O) (e.g., ethanol, isopropyl alcohol, methyl ethyl ketone, methyl isobutyl ketone), or a mixed solution thereof. For example, a Star Burst manufactured by SUGINO MACHINE LIMITED, a Nano Jet Pal manufactured by JOKOH, Inc., a Nano Maker manufactured by Advanced Nano Technology Co., Ltd., or a microfluidizer manufactured by Powrex Corp. is suitable for the wet jet mill processor. Note that an SEM may be used to examine whether or not the carbon material is present in the carbon coating. In a surface image of the composite particles observed using the SEM, each composite particle may have, for example, 5, 10, 20, 30, or 50 pieces of the carbon material or a part thereof in its carbon coating. This number may be any one of the above values or higher, or may be between any two of the above values.

The treatment using a surfactant refers to a method for mixing the above carbon material and a surfactant in a polar solvent such as water or alcohol. Examples of the surfactant include: anionic surfactants such as sodium dodecyl sulfate (SDS); cationic surfactants such as dodecyltrimethylammonium chloride (C_{12}TAC) or hexadecyltrimethylammonium bromide (C_{16}TAB); amphoteric surfactants such as cocamidopropyl betaine or cocamidopropyl hydroxybetaine; and nonionic surfactants such as polyvinyl alcohol or polyoxyethylene octylphenylether (product name: Triton X-100). Note that paragraphs (0015) and (0028) of Patent Literature 10 (JP2005-123107A) disclose acetone as an example of a surfactant. When acetone is used as the surfactant, however, an object of the present invention cannot be achieved because of its volatile nature. Thus, acetone is excluded from the surfactant of the present invention.

The treatment using a polymer dispersant refers to a method for mixing the above carbon material and a polymer dispersant in water or an organic solvent. Examples of the polymer dispersant include polyvinylpyrrolidone (PVP) and poly(allylamine hydrochloride) (PAH).

Examples of the source material for lithium-containing phosphate include: lithium carbonate (Li_2CO_3), lithium hydroxide monohydrate ($LiOH \cdot H_2O$), lithium sulfate monohydrate ($Li_2SO_4 \cdot H_2O$), lithium formate monohydrate ($Li(HCOO) \cdot H_2O$), and/or lithium nitrate ($LiNO_3$); ferric phosphate dihydrate ($FePO_4 \cdot 2H_2O$), ferrous oxalate dihydrate ($FeC_2O_4 \cdot 2H_2O$), ferric sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), and/or ferrous chloride tetrahydrate ($FeCl_2 \cdot 4H_2O$); and phosphoric acid (H_3PO_4), ammonium dihydrogen phosphate ($(NH_4)H_2PO_4$) or ammonium monohydrogen phosphate ($(NH_4)_2HPO_4$), and/or ammonium phosphate ($(NH_4)_3PO_4$).

In addition, lithium manganese phosphate ($LiMnPO_4$) may be produced. In this case, as source material, manganese carbonate ($MnCO_3$), manganese dioxide (MnO_2), manganese sulfate monohydrate ($MnSO_4 \cdot H_2O$), manganese nitrate tetrahydrate ($Mn(NO_3)_2 \cdot 4H_2O$), and/or manganese acetate tetrahydrate ($(CH_3COO)_2Mn \cdot 4H_2O$), for example, may be used to substitute the iron compound such as ferrous oxalate dihydrate, ferric phosphate dihydrate, ferric sulfate heptahydrate, and/or ferrous chloride tetrahydrate in the case of the lithium iron phosphate. Further, lithium manganese iron phosphate ($LiMn_xFe_{(1-x)}PO_4$) may be produced. In this case, source material for the lithium iron phosphate and source material for the lithium manganese phosphate may be used at the same time.

Furthermore, lithium cobalt phosphate ($LiCoPO_4$) may be produced. In this case, as source material, cobalt sulfate heptahydrate ($CoSO_4 \cdot 7H_2O$), for example, may be used to substitute the iron compound in the case of the lithium iron phosphate. Moreover, lithium vanadium phosphate ($Li_3V_2(PO_4)_3$) may be produced. In this case, as source material, divanadium pentoxide (V_2O_5) and/or vanadium oxide sulfate hydride ($VOSO_4 \cdot xH_2O$)($x = 3$ to 4), for example, may be used to substitute the iron compound in the case of the lithium iron phosphate.

In an embodiment of the present invention, examples of the heat-degradable carbon source compound include glucose ($C_6H_{12}O_6$), sucrose ($C_{12}H_{22}O_{11}$), dextrin ($(C_6H_{12}O_5)_n$), ascorbic acid ($C_6H_8O_6$), carboxymethyl cellulose, and coal pitch.

In an embodiment of the present invention, a mixer may be used for the mixing. Examples of the mixer include a tank with a mixer, a sonicator, and a homogenizer. In this case, water, alcohol, or a mixed solvent of water and alcohol is suitable for the solvent. Note that when a surfactant or a polymer dispersant is used for surface treatment, pretreatment may be carried out before the source material is mixed or treatment may be carried out at the same time when the source material is mixed.

In an embodiment of the present invention, it is preferable to perform a method for heating a solution having dissolved therein a lithium ion (Li^+), a phosphate ion (PO_4^{3-}), and a metal ion other than from lithium, and/or a heat-degradable carbon source compound, etc., as a solution state while stirring in a tank with a mixer, etc. The heating temperature is preferably from 60 to 100°C. In order to increase a reaction rate, however, it is preferable to use a method using a pressured and heated solvent at from 100 to 250°C (i.e., a hydrothermal synthesis method). In this case, the heating is carried out using a pressure-resistant vessel such as an autoclave. This heating temperature may be, for example, 60, 80, 100, 150, 200, or 250°C. The temperature may be between any two of the above values. In this case, depending on the need, a pH modifier such as ammonia (NH_3), phosphoric acid (H_3PO_4), or sulfuric acid (H_2SO_4) may be added to a solution having dissolved therein a lithium ion (Li^+), a phosphate ion (PO_4^{3-}), and a metal ion other than from lithium, and/or a heat-degradable carbon source compound, etc.

In an embodiment of the present invention, the final heating is preferably carried out *in vacuo* under an inert atmosphere, reducing atmosphere, or mixed atmosphere of an inert gas and a reducing gas to form composite particles coated with carbon coating containing carbon material. Examples of the inert gas include argon (Ar), helium (He), and nitrogen (N_2). Examples of the reducing gas include hydrogen (H_2) and ammonia (NH_3). The heating temperature is preferably from 400 to 900°C and more preferably from 500 to 800°C. This heating temperature may be, for example, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, or 900°C. The temperature may be between any two of the above values.

Composite particles according to an embodiment of the present invention, a conduction aid, and a binder may be mixed to form an electrode material for a lithium-ion secondary battery. Examples of the conduction aid used include: carbon black such as acetylene black or furnace black, and/or a carbon nanotube or carbon nanofiber. Polyvinylidene fluoride (PVDF) may be used as the binder. With regard to a mixing ratio in an embodiment of the present invention, the composite particles have, for example, 60 to 95% by mass and the remainder consists of the conduction aid and the binder. When the composite particles are less than 60% by mass, the lithium-ion secondary battery has a reduced charge/discharge capacity. In addition, when the composite particles are more than 95% by mass, the amount of the conduction aid is insufficient. This increases the electric resistance of a positive electrode. In addition, the insufficient amount of the binder causes insufficient firmness of the positive electrode. Unfortunately, this results in a problem that the positive electrode material is likely to detach from a collector (mostly made of aluminum) during charge and discharge.

In an embodiment of the present invention, a positive electrode material is used for a positive electrode formed on a collector and the positive electrode may be used for a lithium-ion secondary battery. Examples of other components used for the lithium-ion secondary battery include a separator, an electrolytic solution, and a negative electrode material. The separator electrically insulates the positive electrode from the negative electrode and helps retain the electrolytic solution. Separators made of synthetic resin such as polyethylene and polypropylene may be used. In order to increase retention of the electrolytic solution, a porous film is preferably used for the separators.

In addition, in a lithium secondary battery using a positive electrode according to an embodiment of the present invention, a lithium salt-containing nonaqueous electrolytic solution or ion conductive polymer may be preferably used as an electrolytic solution in which a group of the electrodes is soaked. Examples of a nonaqueous solvent for a nonaqueous electrolyte in the lithium salt-containing nonaqueous electrolytic solution include ethylene carbonate (EC), propylene carbonate (PC), diethyl carbonate (DEC), dimethyl carbonate (DMC), and methylethyl carbonate (MEC). In addition, examples of the lithium salt capable of being dissolved in the above nonaqueous solvent include lithium hexafluorophosphate ($LiPF_6$), lithium tetrafluoroborate ($LiBF_4$), and lithium trifluoromethanesulfonate ($LiSO_3CF_3$).

A preferable active substance of a negative electrode is a material that can reversibly store and release a Li ion in the same manner as in the case of the positive electrode, has poor reactivity with the electrolyte, and has a less redox potential than the positive electrode material. Examples include graphite, lithium titanate, silicon (Si), and tin (Sn). Two or more of them may be combined depending on the need. These compounds may be combined with a conduction aid and a binder in the same manner as in the case of the positive electrode, and may be practically used as a negative electrode material formed on a collector (in the case of the negative electrode, copper is mainly used).

The material members disclosed in paragraphs (0027) to (0029) are combined. Then, in order to prevent damage, deformation, and contact with an ambient air, the members are sealed in a container to form a lithium-ion secondary battery. The shape and material of the container are appropriately selected depending on its usage. For example, when charge and discharge characteristics, for example, are tested in a simple way, it is preferable to form a coin cell using a disk container made of metal such as stainless for sealing.

A high capacity and long service life may be required for industrial or consumer use. In this case, a positive electrode material, a separator, and a negative electrode material are alternately wound to form a wound cell using a metal cylinder-type or rectangular-type container for sealing. In the case of intermediate usage, a positive electrode material, a separator, and a negative electrode material are alternately stacked to form a laminated cell (aluminum pouch cell) using an aluminum-laminated package, etc., for sealing.

Examples

The following details composite particles, a process for producing the same, electrode material for a secondary battery and a secondary battery according to the present invention by referring to Examples and Comparative Examples. The present invention, however, is not limited to the following Examples without departing from the scope of the present invention.

Examples 1 to 7

(Surface Treatment of Carbon Material)

Tables 1 and 2 list carbon materials used for treatment and treatment methods. Note that organic functional groups introduced onto a surface of the carbon materials by oxidation treatment were determined by temperature-programmed desorption gas chromatography/mass spectrometry (a TDS-GC/MS method) using a temperature-programmed desorption device (Double-Shot Pyrolyzer 7683B manufactured by Agilent Technologies Inc.), gas chromatography equipment (HP6890 manufactured by Hewlett-Packard Development Company, L.P.), and a mass spectrometer (5973 manufactured by Hewlett-Packard Development Company, L.P.). Qualitative analysis was performed by examining whether or not there were mass spectral peaks of water (mass number = 18), carbon monoxide (mass number = 28), and carbon dioxide (mas number = 44). Note that a mass spectrum detected below 200°C was considered to be due to detachment of adsorbed gas. Accordingly, the mass spectrum was neglected. In addition, the same condition as of the temperature-programmed desorption device (i.e., heating *in vacuo* at a temperature increasing rate of 25°C/min from 200°C to 1000°C) was applied to heat 10 g of the carbon materials in an electric furnace and to determine a change in mass before and after the heating. The following equation was used to calculate an amount of decrease in mass and the amount was defined as a content of the organic functional groups.

[Organic functional group content (% by mass)] = [{(Mass of carbon material after heating at 200°C) - (Mass of carbon material after heating at 1000°C)} / (Mass of carbon material after heating at 200°C)] X 100

Table 1

Example	Carbon Material	Product Name	Manufacturer	Average Fiber Size or Average Primary Particle Size	Carbon Material Linking Method	Carbon Material Linking Conditions		Surface Treatment Method	Surface Treatment Condition		Organic Functional Group Type*	Amount of Organic Functional Group
1	Carbon nanofiber	CNF-T	Mitsubishi Materials Electronic Chemicals Co., Ltd.	15nm	–	–	–	Oxidation treatment (Adding nitric acid while heating in sulfuric acid)	CNF-T : 500g Sulfuric acid : 5L 60% Nitric acid : 1.8L	100℃ 3 hour stirring	-OH >C=O -COOH	1.2% by mass
2	Acetylene black	HS-100	DENKI KAGAKU KOGYO KABUSHIKI KAISHA	60nm	–	–	–	Treatment with polymer dispersant polyvinylpyrrolidone (PVP)	HS-100 : 500g PVP(K-30 manufactured by NIPPON SHOKUBAI CO., LTD.) : 50g Distilled water : 10L	60℃ 6 hour stirring	–	–
3	Particles produced by linking carbon nanofiber and acetylene black	CNF-T Acetylene black	Mitsubishi Materials Electronic Chemicals Co., Ltd.(CNF-T) (Acetylene black : generated from C_2H_2 gas)	15nm (CNF-T average fiber size) 50nm (Acetylene black average primary particle size)	Powder CNF-T was injected into AB-generating site to precipitate AB on NF-T surface	CNF-T feed rate : 500g/hr C_2H_2 feed rate : 30L/min N_2(dilution gas) feed rate : 400L/min	2000℃ 1hr	Treatment with surfactant polyoxyethylene octylphenylether (TritonX-100)	Particles produced by linking CNF-T and acetylene black : 500g TritonX-100 (manufactured by Roche Applied Science) : 25mL Distilled water : 10L	30℃ 2 hour stirring	–	–
4	Particles produced by linking carbon nanofiber and acetylene black	Carbon nanofiber AB	(Carbon nanofiber : generated from CO gas) DENKI KAGAKU KOGYO KABUSHIKI KAISHA(AB)	20nm (Carbon nanofiber average fiber size) 40nm (AB average primary particle size)	AB was injected into carbon nanofiber-generating site to precipitate carbon nanofiber on AB surface	AB : 30g Cobalt oxide powder (Sigma-Aldrich 637025 ; Particle size 50nm or less) : 1g CO feed rate : 1.6L/min H_2 feed rate : 0.6L/min N_2(dilution gas) feed rate : 0.8L/min	600℃ 3hr	Treatment with surfactant sodium dodecyl sulfate (SDS)	Particles produced by linking carbon nanofiber and AB : 60g SDS(Sigma-Aldrich 71717) : 5g Distilled water : 1L	30℃ 2 hour stirring	–	–

*Regarding types of organic functional groups, H_2O, CO, and CO_2 detected by TDS-GC/MS method were presumed to be attributed to -OH, >C=O, and -COOH groups, respectively.

Table 2

Example	Carbon Material	Product Name	Manufacturer	Average Fiber Size or Average Primary Particle Size	Carbon Material Linking Method	Carbon Material Linking Conditions		Surface Treatment Method	Surface Treatment Condition		Organic Functional Group Type*	Amount of Organic Functional Group
5	Particles produced by linking carbon nanofiber (two kinds) and acetylene black	VGCF-H	SHOWA DENKO K.K.(VGCF-H)	150nm (VGCF-H average fiber size)	Mixing with wet vibrating mill	VGCF-H : 25g CNF-T : 25g HS-100 : 50g Ethanol : 1L Al_2O_3 ball : 1kg	Mixing period : 1hr	Oxidation treatment (Treatment using wet jet mill [Star Burst manufactured by SUGINO MACHINE LIMITED])	Particles produced by linking VGCF-H/CNF-T/Acetylene black : 100g Ethanol : 1L (using post-mixing solution as it was)	30℃ Ejecting pressure : 180MPa The number of ejecting paths : 5	-OH >C=O -COOH	1.0% by mass
		CNF-T	Mitsubishi Materials Electronic Chemicals Co., Ltd.(CNF-T)	15nm (CNF-T average fiber size)								
		HS-100	DENKI KAGAKU KOGYO KABUSHIKI KAISHA(HS-100)	60nm (HS-100 average primary particle size)								
6	Particles produced by linking carbon nanofiber and acetylene black	CNF-T	Mitsubishi Materials Electronic Chemicals Co., Ltd.	15nm (CNF-T average fiber size)	Mixing with wet vibrating mill	CNF-T : 20g HS-100 : 80g Ethanol : 1L Al_2O_3 ball : 1kg	Mixing period : 1hr	Oxidation treatment (Stirring in ozone-containing water)	Particles produced by linking CNF-T/HS-100 : 100g Ozone level : 50ppm Distilled water : 2L	30℃ 6 hour stirring	-OH >C=O -COOH	1.8% by mass
		HS-100	DENKI KAGAKU KOGYO KABUSHIKI KAISHA	60nm (HS-100 average primary particle size)								
7	Furnace black	Super-P	TIMCAL Inc.	40nm	–	–	–	Treatment with polymer dispersant poly(allylamine hydrochloride)(PAH)	Super-P : 300g PAH(Sigma-Aldrich 283215, average molecular weight: 15000) : 20g Distilled water : 10L	40℃ 6 hour stirring	–	–

*Regarding types of organic functional groups, H_2O, CO, and CO_2 detected by TDS-GC/MS method were presumed to be attributed to -OH, >C=O, and -COOH groups, respectively.

Examples 8 to 10

(Mixing and Heating of Surface-treated Carbon Material, Source Material for Lithium-containing Phosphate, and Heat-degradable Carbon Source Compound)

The surface-treated carbon material as prepared in Examples 1 to 3, source material, and a carbon source compound were mixed and heated under conditions designated in Table 3.

Table 3

Example	Carbon Material	Source Material for Lithium-containing Phosphate•Solvent•Carbon Source Material, etc.	Mixing Method	Mixing Conditions	Heating Method	Heating Conditions
8	Example 1 : 10g	LiOH·H_2O(Sigma-Aldrich 402974) : 126g $FeSO_4$·$7H_2O$(Sigma-Aldrich 44982) : 278g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Ascorbic acid (Sigma-Aldrich P5811) : 35g Distilled water : 1L	Mixing with mixer	30°C 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	190°C 12hr
9	Example 2 : 10g	LiOH·H_2O(Sigma-Aldrich 402974) : 126g $MnSO_4$ · H_2O(Sigma-Aldrich M7634) : 169g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Carboxymethyl cellulose (Grade A; NIPPON PAPER INDUSTRIES CHEMICAL Div.) : 30g Distilled water : 0.7L Ethanol : 0.3L	Mixing with mixer	30°C 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	170°C 12hr
10	Example 3 : 10g	LiOH·H_2O(Sigma-Aldrich 402974) : 126g $FeSO_4$·$7H_2O$(Sigma-Aldrich 44982) : 93g $MnSO_4$ · H_2O(Sigma-Aldrich M7634) : 113g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Glucose (Sigma-Aldrich 158968) : 20g Distilled water : 1L	Mixing with mixer	30°C 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	190°C 12hr

*Method for drying after heating: Spray dry

Examples 11 to 13

(Method for Forming Particles of Lithium-containing Phosphate and/or Particles of Precursor Thereof and Mixing of Surface-treated Carbon Material, Particles of Lithium-containing Phosphate and/or Particles of Precursor Thereof, and Carbon Source Compound)

Table 4 shows a method for forming particles of lithium-containing phosphate and/or particles of a precursor thereof from source material. The particles formed, the surface-treated carbon material, and a carbon source compound were mixed under conditions designated in Table 4.

Example 14

(Mixing of Surface-treated Carbon Material, Particles of Lithium-containing Phosphate, and Carbon Source Compound)

The surface-treated carbon material as prepared in Example 7, Particles of lithium-containing phosphate, and a carbon source compound were mixed under conditions designated in Table 4.

Table 4

Example	Method for Forming Particles of Lithium-containing Phosphate and/or Particles of Precursor Thereof						Carbon Material Mixed	Carbon Source Compound Mixed	Mixing Method, etc.
	Source Material for Lithium-containing Phosphate · Solvent · Carbon Source Material	Mixing Method	Mixing Conditions	Heating Method	Heating Conditions	Particles Formed			
11	$LiOH\cdot H_2O$(Sigma-Aldrich 402974) : 126g $CoSO_4\cdot 7H_2O$(Sigma-Aldrich C6768) : 281g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Distilled water : 1L	Mixing with mixer	30℃ 1hr	Heating while mixing with mixer	90℃ 24hr	$LiCoPO_4$ Precursor (Hydrate)	Example 4 : 10g	Sucrose (Sigma-Aldrich 84097) : 20g	A solution after heating at 90℃ for 24 hr was filtered, washed, and dried in vacuo to produce powder. Then, 100 g of the powder recovered and carbon material were dispersed in 500 mL of distilled water while sucrose was added. The mixture was stirred in a tank with a mixer for 30 min, the mixture was dried with a spray dryer.
12	$Li_2SO_4\cdot H_2O$ (Sigma-Aldrich 62609) : 192g $VOSO_4\cdot nH_2O$ (n=3~4) (Wako Pure Chemical Industries 227-01015) : 151g $(NH_4)_2HPO_4$ (Sigma-Aldrich215996) : 132g H_2SO_4 (Sigma-Aldrich320501) : 0.01g Distilled water : 1L	Mixing with mixer	30℃ 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	190℃ 12hr	$Li_3V_2(PO_4)_3$	Example 5 : 10g	Glucose (Sigma-Aldrich 158968) : 20g	A solution after heating at 190℃ for 12 hr was filtered, washed, and dried in vacuo to produce powder. Then, 100 g of the powder recovered and carbon material were dispersed in 500 mL of distilled water while glucose was added. After the mixture was stirred with a rotating homogenizer (Auto Mixer Model 20 manufactured by PRIMIX Corporation) for 30 min, the mixture was dried under reduced pressure while heated at 100℃.
13	$LiOH\cdot H_2O$(Sigma-Aldrich 402974) : 126g $FeSO_4\cdot 7H_2O$(Sigma-Aldrich 44982) : 278g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Distilled water : 1L	Mixing with mixer	30℃ 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	190℃ 12hr	$LiFePO_4$	Example 6 : 10g	Carboxymethyl cellulose (Grade A; NIPPON PAPER INDUSTRIES CHEMICAL Div.) : 20g	A solution after heating at 190℃ for 12 hr was filtered, washed, and dried in vacuo to produce powder. Then, 100 g of the powder recovered and carbon material were dispersed in a mixed solution of 300 mL of distilled water and 200 ml of ethanol while CMC was added. After the mixture was stirred with a ultrasonic homogenizer (BRANSON Model 4020-800) for 30 min, the mixture was dried under reduced pressure while heated at 100℃.
14	$LiFePO_4$ (Phostech Lithium inc. P2) : 100g	—	—	—	—	—	Example 7 : 10g	Sucrose (Sigma-Aldrich 84097) : 20g	100g of particles of $LiFePO_4$ and carbon material were dispersed in 500 mL of distilled water while sucrose was added. After the mixture was stirred with a rotating homogenizer (Auto Mixer Model 20 manufactured by PRIMIX Corporation) for 30 min, the mixture was dried under reduced pressure while heated at 100℃.

Examples 15 to 21

(Further Heating)

The mixture containing the surface-treated carbon material, a lithium-containing phosphate precursor and/or lithium-containing phosphate, and a carbon source compound, which mixture was produced in Examples 8 to 14, was further heated under conditions designated in Table 5 to prepare composite particles according to an example of the present invention. The crystal phase of the composite particles was identified by powder X - ray diffraction (using an X-ray diffractometer RU-200A manufactured by Rigaku Corporation; an X-ray source: Cu-Kα; a voltage: 40 kV; a current: 30 mA). In addition, a scanning electron microscope (a scanning electron microscope (SEM) JSM-6301F manufactured by JEOL Ltd.; an acceleration voltage: 1 kV; magnification: 10,000 to 50,000 x) was used to measure an average primary particle size of the composite particles and to inspect whether or not the carbon material was included in the carbon coating on the particle surface.

Table 5

	Heated Mixture	Heating Temperature・Time	Heating Atmosphere	Crystal Phase of Product	Average Primary Particle Size	Presence of Carbon Material in Carbon Coating
Example 15	Example 8 : 100g was recovered	800℃ 1hr	In vacuo	$LiFePO_4$	0.1 μm	Yes
Example 16	Example 9 : 100g was recovered	600℃ 3hr	N_2	$LiMnPO_4$	0.5 μm	Yes
Example 17	Example 10 : 100g was recovered	800℃ 1hr	$N_2:H_2=7:3$	$LiMn_{0.67}Fe_{0.33}PO_4$	0.1 μm	Yes
Example 18	Example 11 : 100g was recovered	700℃ 1hr	In vacuo	$LiCoPO_4$	0.05 μm	Yes
Example 19	Example 12 : 100g was recovered	800℃ 2hr	$Ar:H_2=4:1$	$Li_3V_2(PO_4)_3$	10 μm	Yes
Example 20	Example 13 : 100g was recovered	700℃ 2hr	Ar	$LiFePO_4$	0.5 μm	Yes
Example 21	Example 14 : 100g was recovered	700℃ 2hr	Ar	$LiFePO_4$	0.7 μm	Yes
Comparative Example 15	Comparative Example 8 : 100g was recovered	800℃ 1hr	In vacuo	$LiFePO_4$	0.1 μm	No
Comparative Example 16	Comparative Example 9 : 100g was recovered	600℃ 3hr	N_2	$LiMnPO_4$	0.5 μm	No
Comparative Example 17	Comparative Example 10 : 100g was recovered	800℃ 1hr	$N_2:H_2=7:3$	$LiMn_{0.67}Fe_{0.33}PO_4$	0.1 μm	No
Comparative Example 18	Comparative Example 11 : 100g was recovered	700℃ 1hr	In vacuo	$LiCoPO_4$	0.05 μm	No
Comparative Example 19	Comparative Example 12 : 100g was recovered	800℃ 2hr	$Ar:H_2=4:1$	$Li_3V_2(PO_4)_3$	10 μm	No
Comparative Example 20	Comparative Example 13 : 100g was recovered	700℃ 2hr	Ar	$LiFePO_4$	0.5 μm	No
Comparative Example 21	Comparative Example 14 : 100g was recovered	700℃ 2hr	Ar	$LiFePO_4$	0.7 μm	No

Comparative Examples 1 to 21

The carbon material was not subjected to surface treatment and the same as of Examples 1 to 21 applied to the other processes to prepare particles of Comparative Examples 15 to 21. Tables 5 to 9 show these conditions and results together.

Table 6

Comparative Example	Carbon Material	Product Name	Manufacturer	Average Fiber Size or Average Primary Particle Size	Carbon Material Linking Method	Carbon Material Linking Conditions		Surface Treatment Method	Organic Functional Group Type*
1	Carbon nanofiber	CNF-T	Mitsubishi Materials Electronic Chemicals Co., Ltd.	15nm	—	—	—	—	—
2	Acetylene black	HS-100	DENKI KAGAKU KOGYO KABUSHIKI KAISHA	60nm	—	—	—	—	—
3	Particles produced by linking carbon nanofiber and acetylene black	CNF-T Acetylene black	Mitsubishi Materials Electronic Chemicals Co., Ltd.(CNF-T) (Acetylene black : generated from C2H2 gas)	15nm (CNF-T average fiber size) 50nm(Acetylene black average primary particle size)	Powder CNF-T was injected into AB-generating site to precipitate AB on CNF-T surface	CNF-T feed rate : 500g/hr C_2H_2 feed rate : 30L/min N_2(dilution gas) feed rate : 400L/min	2000℃ 1hr	—	—
4	Particles produced by linking carbon nanofiber and acetylene black	Carbon nanofiber AB	(Carbon nanofiber : generated from CO gas) : DENKI KAGAKU KOGYO KABUSHIKI KAISHA(AB)	20nm (Carbon nanofiber average fiber size) 40nm(AB average primary particle size)	AB was injected into carbon nanofiber-generating site to precipitate carbon nanofiber on AB surface	AB : 30g Cobalt oxide powder(Sigma-Aldrich 637025 : Particle size 50nm or less) : 1g CO feed rate : 1.6L/min H_2 feed rate : 0.6L/min N_2(dilution gas) feed rate : 0.8L/min	600℃ 3hr	—	—
5	Particles produced by linking carbon nanofiber (two kinds) and acetylene black	VGCF-H CNF-T HS-100	SHOWA DENKO K.K.(VGCF-H) Mitsubishi Materials Electronic Chemicals Co., Ltd.(CNF-T) DENKI KAGAKU KOGYO KABUSHIKI KAISHA(HS-100)	150nm(VGCF-H average fiber size) 15nm(CNF-T average fiber size) 60nm(HS-100 average primary particle size)	Mixing with wet vibrating mill	VGCF-H : 25g CNF-T : 25g HS-100 : 50g Ethanol : 1L Al_2O_3 ball : 1kg	Mixing period : 1hr	—	—
5	Particles produced by linking carbon nanofiber and acetylene black	CNF-T HS-100	Mitsubishi Materials Electronic Chemicals Co., Ltd. DENKI KAGAKU KOGYO KABUSHIKI KAISHA	15nm (CNF-T average fiber size) 60nm(HS-100 average primary particle size)	Mixing with wet vibrating mill	CNF-T : 20g HS-100 : 80g Ethanol : 1L Al_2O_3 ball : 1kg	Mixing period : 1hr	—	—
7	Furnace black	Super-P	TIMCAL Inc.	40nm	—	—	—	—	—

*Regarding types of organic functional groups, H_2O, CO, and CO_2 detected by TDS-GC/MS method were presumed to be attributed to -OH, >C=O, and -COOH groups, respectively.

Table 7

Comparative Example	Carbon Material	Source Material for Lithium-containing Phosphate • Solvent • Carbon Source Material	Mixing Method	Mixing Conditions	Heating Method	Heating Conditions
8	Comparative Example 1 : 100g	$LiOH \cdot H_2O$(Sigma-Aldrich 402974) : 126g $FeSO_4 \cdot 7H_2O$(Sigma-Aldrich 44982) : 278g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Ascorbic acid (Sigma-Aldrich P5811) : 35g Distilled water : 1L	Mixing with mixer	30°C 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	190°C 12hr
9	Comparative Example 2 : 10g	$LiOH \cdot H_2O$(Sigma-Aldrich 402974) : 126g $MnSO_4 \cdot H_2O$(Sigma-Aldrich M7634) : 169g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Carboxymethyl cellulose (Grade A; NIPPON PAPER INDUSTRIES CHEMICAL Div.) : 30g Distilled water : 0.7L Ethanol : 0.3L	Mixing with mixer	30°C 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	170°C 12hr
10	Comparative Example 3 : 10g	$LiOH \cdot H_2O$(Sigma-Aldrich 402974) : 126g $FeSO_4 \cdot 7H_2O$(Sigma-Aldrich 44982) : 93g $MnSO_4 \cdot H_2O$(Sigma-Aldrich M7634) : 113g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Glucose (Sigma-Aldrich 158968) : 20g Distilled water : 1L	Mixing with mixer	30°C 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	190°C 12hr

*Method for drying after heating: Spray dry

Table 8

Comparative Example	Method for Forming Particles of Lithium-containing Phosphate and/or Particles of Precursor Thereof						Carbon Material Mixed	Carbon Source Compound Mixed	Mixing Method, etc.
	Source Material for Lithium-containing Phosphate・Solvent・Carbon Source Material	Mixing Method	Mixing Conditions	Heating Method	Heating Conditions	Particles Formed			
11	$LiOH \cdot H_2O$(Sigma-Aldrich 402974) : 126g $CoSO_4 \cdot 7H_2O$(Sigma-Aldrich C6768) : 281g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Distilled water : 1L	Mixing with mixer	30℃ 1hr	Heating while mixing with mixer	90℃ 24hr	$LiCoPO_4$ Precursor (Hydrate)	Comparative Example 4 : 10g	Sucrose (Sigma-Aldrich 84097) : 20g	A solution after heating at 90℃ for 24 hr was filtered, washed, and dried in vacuo to produce powder. Then, 100 g of the powder recovered and carbon material were dispersed in 500 mL of distilled water while sucrose was added. The mixture was stirred in a tank with a mixer for 30 min, the mixture was dried with a spray dryer.
12	$Li_2SO_4 \cdot H_2O$ (Sigma-Aldrich 62609) : 192g $VOSO_4 \cdot nH_2O$ (n=3~4) (Wako Pure Chemical Industries 227-01015) : 151g $(NH_4)_2HPO_4$ (Sigma-Aldrich215996) : 132g H_2SO_4 (Sigma-Aldrich320501) : 0.01g Distilled water : 1L	Mixing with mixer	30℃ 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	190℃ 12hr	$Li_3V_2(PO_4)_3$	Comparative Example 5 : 10g	Glucose (Sigma-Aldrich 158968) : 20g	A solution after heating at 190℃ for 12 hr was filtered, washed, and dried in vacuo to produce powder. Then, 100 g of the powder recovered and carbon material were dispersed in 500 mL of distilled water while glucose was added. After the mixture was stirred with a rotating homogenizer (Auto Mixer Model 20 manufactured by PRIMIX Corporation) for 30 min, the mixture was dried under reduced pressure while heated at 100℃.
13	$LiOH \cdot H_2O$(Sigma-Aldrich 402974) : 126g $FeSO_4 \cdot 7H_2O$(Sigma-Aldrich 44982) : 278g $(NH_4)_2HPO_4$(Sigma-Aldrich 215996) : 10g H_3PO_4(Sigma-Aldrich P5811) : 91g Distilled water : 1L	Mixing with mixer	30℃ 1hr	Heating in autoclave while mixing with mixer (hydrothermal treatment)	190℃ 12hr	$LiFePO_4$	Comparative Example 6 : 10g	Carboxymethyl cellulose (Grade A; NIPPON PAPER INDUSTRIES CHEMICAL Div.) : 20g	A solution after heating at 190℃ for 12 hr was filtered, washed, and dried in vacuo to produce powder. Then, 100 g of the powder recovered and carbon material were dispersed in a mixed solution of 300 mL of distilled water and 200 ml of ethanol while CMC was added. After the mixture was stirred with a ultrasonic homogenizer (BRANSON Model 4020-800) for 30 min, the mixture was dried under reduced pressure while heated at 100℃.
14	$LiFePO_4$ (Phostech Lithium inc. P2) : 160g	–	–	–	–	–	Comparative Example 7 : 10g	Sucrose (Sigma-Aldrich 84097) : 20g	100g of particles of $LiFePO_4$ and carbon material were dispersed in 500 mL of distilled water while sucrose was added. After the mixture was stirred with a rotating homogenizer (Auto Mixer Model 20 manufactured by PRIMIX Corporation) for 30 min, the mixture was dried under reduced pressure while heated at 100℃.

The composite particles of Examples 15 to 21, carbon as a conduction aid, and polyvinylidene fluoride (a KF polymer solution manufactured by KUREHA CORPORATION) as a binder were combined at predetermined ratios designated in Table 9. N-methylpyrrolidone (catalog No. 328634 manufactured by Sigma-Aldrich Co. LLC.) was added thereto as a dispersion solvent. Then, the mixture was kneaded to prepare a positive electrode combination (slurry). This combination was used as positive electrode material to manufacture a laminated cell. After that, its charge and discharge characteristics were evaluated. The following shows an example of a method for manufacturing a positive electrode and a laminated cell. First, the composite particles of Examples 15 to 21 were used as a positive electrode combination slurry. Next, an aluminum foil with a thickness of 20 µm was coated with this slurry and dried. Then, the foil was pressed and cut at 40 mm x 40 mm to prepare a positive electrode for a lithium secondary battery. Graphite (synthetic graphite MCMB6-28 manufactured by OSAKA GAS CO., Ltd.) was used for a negative electrode. Polyvinylidene fluoride as a binder was mixed at a predetermined ratio. Then, a slurry was prepared in the same manner as in the case of the positive electrode. Subsequently, a copper foil with a thickness of 10 µm was coated with this slurry and dried. After that, the foil was pressed and cut at 45 mm x 45 mm to manufacture a negative electrode for a lithium secondary battery. An olefin fiber nonwoven fabric with a size of 50 mm x 50 mm was used as a separator that electrically separate the positive electrode from the negative electrode. An electrolytic solution was a solution prepared by mixing EC (ethylene carbonate manufactured by Aldrich Inc.) and MEC (methylethyl carbonate manufactured by Aldrich Inc.) at a volume ratio of 30:70 and by dissolving lithium hexafluorophosphate (LiPF$_6$ manufactured by Stella Chemifa Corporation) at 1 mol/L in the solution. After terminals were connected to the positive and negative electrodes, the whole body was enclosed in an aluminum-laminated package to form a laminated cell with a size of 60 mm x 60 mm.

Discharge performance of the cell was tested as follows. First, a cell was initially charged. Next, its charge/discharge efficiency was verified to be at or near 100%. Then, a constant current was discharged at a current density of 0.7 mA/cm^2 until the voltage reached 2.1 V. At that time, the discharge capacity was measured. After that, the discharge capacity was divided by an amount of positive electrode active substance to calculate a capacity density (mAh/g). A current level that can charge and discharge this capacity (mAh) in 1 hour was defined as "1C".

After the initial charge and discharge, its charge was conducted at 4.2 V (4.8 V was used for Examples 25 and 26 and Comparative Examples 25 and 26)(at a constant current of 0.2C; terminated when a current was 0.05C). With regard to the discharge, a current level in each cycle was gradually increased from 0.2C, 0.33C, 0.5C, 1C, to 3C (at a constant current; terminated when the voltage was 2.1

V). A 10-min interval was placed between the cycles, and the cycle was then repeated while keeping a current level of 3C. A cycle characteristic was defined as a ratio of a charge/discharge capacity at cycle 1000 of 3C to a charge/discharge capacity at the initial cycle (0.2C). Further, I-V characteristics at a SOC (charge depth) of 50% were used to calculate direct current resistance (DCR) of the cell. The direct current resistance during charge was defined as "charge DCR" and the direct current resistance during discharge was defined as "discharge DCR". Table 9 lists these results.

Comparative Examples 22 to 28

Except using the composite particles of Comparative Examples 15 to 21 as alternatives for those of Examples 15 to 21, the same procedure as in Examples 22 to 28 was applied to form a laminated cell. Then, the discharge performance of the cell was tested. Table 9 shows the results.

Table 9

	Composite Particles Used	Positive Electrode Combination	Negative Electrode Combination	Capacity Density (mAh/g)	3C/0.2C Cycle Characteristic (%)	Charge DCR (mΩ)	Discharge DCR (mΩ)
Example 22	Example 15	Composite particles : 85% by mass Conduction aid[*1] : 9% by mass Binder[*2] : 6% by mass	Graphite : 94% by mass Conduction aid[*3] : 1% by mass Binder[*4] : 5% by mass	155	91	1190	1322
Example 23	Example 16			80	74	2468	2525
Example 24	Example 17			125	81	1812	1834
Example 25	Example 18			135	87	1210	1367
Example 26	Example 19			130	71	1688	1789
Example 27	Example 20			150	78	1312	1444
Example 28	Example 21			160	86	1230	1386
Comparative Example 22	Comparative Example 15			150	58	1754	1999
Comparative Example 23	Comparative Example 16			70	47	3706	3759
Comparative Example 24	Comparative Example 17			120	50	2743	2840
Comparative Example 25	Comparative Example 18			130	52	1854	2094
Comparative Example 26	Comparative Example 19			125	41	2654	2703
Comparative Example 27	Comparative Example 20			145	49	2002	2185
Comparative Example 28	Comparative Example 21			155	54	1843	2084

[*1] Powder obtained by mixing CNF-T (Mitsubishi Materials Corporation) and HS-100 (DENKI KAGAKU KOGYO KABUSHIKI KAISHA) at a mass ratio of 1:4 was used as the conduction aid for a positive electrode.

[*2] The binder for a positive electrode was polyvinylidene fluoride (PVDF) L#7208 manufactured by KUREHA CORPORATION (% by mass was a value converted to a solid content).

[*3] The conduction aid for a negative electrode was VGCF-H (SHOWA DENKO K.K.).

[*4] The binder for a negative electrode was PVDF L#9130 manufactured by KUREHA CORPORATION (% by mass was a value converted to a solid content).

It has been found from Examples and Comparative Examples that cells using composite particles according to the present invention have remarkable improvements in the cycle characteristic determined by the discharge performance test.

Industrial Applicability

Positive electrode material for a lithium-ion secondary battery according to the present invention has excellent electron conductivity while using lithium-containing phosphate as a positive electrode active substance and overcoming its drawback. The lithium-containing phosphate should be heat-stable and highly safe, but has the drawback that its resistance is high. The positive electrode material of the present invention has resolved the drawback of the lithium-containing phosphate. As a result, it is possible to manufacture a highly safe lithium-ion secondary battery capable of maintaining stable charge and discharge characteristics over a long period of service life. A lithium-ion secondary battery using positive electrode material of the present invention can be suitably used for application such as an electric tool and a hybrid car, which require stable charge and discharge over a long period.

Claims

1. Composite particles comprising:

particles of lithium-containing phosphate; and

carbon coating comprising at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material,

wherein each particle is coated with the carbon coating.

2. The composite particles according to Claim 1, wherein the fibrous carbon material is a carbon nanotube with an average fiber size of 5 to 200 nm.

3. The composite particles according to Claim 1 or 2, wherein the chain-like carbon material is carbon black produced by linking, like a chain, primary particles with an average particle size of 10 to 100 nm.

4. The composite particles according to any one of Claims 1 to 3, wherein the lithium-containing phosphate is $LiFePO_4$, $LiMnPO_4$, $LiMn_XFe_{(1-X)}PO_4$, $LiCoPO_4$, or $Li_3V_2(PO_4)_3$.

5. The composite particles according to any one of Claims 1 to 4, wherein primary particles have an average size of 0.02 to 20 μm.

6. A process for producing the composite particles according to any one of Claims 1 to 5, the process comprising:

a first step of subjecting to surface treatment at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material;

a second step of dispersing and mixing the at least one surface-treated carbon material in a solution having dissolved in a solvent a lithium ion (Li^+), a phosphate ion (PO_4^{3-}), and a metal ion other than from lithium, and a heat-degradable carbon source compound;

a third step of heating the mixture as a solution state; and

a fourth step of drying and further heating the mixture to form composite particles, wherein each particle of lithium-containing phosphate is coated with carbon coating comprising the at least one carbon material.

7. A process for producing the composite particles according to any one of Claims 1

to 5, the process comprising:

a first step of subjecting to surface treatment at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material;

a second step of heating a solution having dissolved in a solvent a lithium ion (Li^+), a phosphate ion (PO_4^{3-}), and a metal ion other than from lithium as a solution state to form particles of lithium-containing phosphate and/or particles of a precursor thereof;

a third step of mixing the at least one surface-treated carbon material obtained in the first step, the particles obtained in the second step, and a heat-degradable carbon source compound; and

a fourth step of heating the mixture to form composite particles, wherein each particle of lithium-containing phosphate is coated with carbon coating comprising the at least one carbon material.

8. The process for producing composite particles according to Claim 6 or 7, wherein the solvent is water, alcohol, or a mixed solvent of water and alcohol.

9. The process for producing composite particles according to any one of Claims 6 to 8, wherein a method using a pressured and heated solvent is used for the third step of Claim 6 or the second step of Claim 7.

10. A process for producing the composite particles according to any one of Claims 1 to 5, the process comprising:

a first step of subjecting to surface treatment at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material;

a second step of mixing the at least one surface-treated carbon material, particles of lithium-containing phosphate, and a heat-degradable carbon source compound; and

a third step of heating the mixture to form composite particles, wherein each particle of lithium-containing phosphate is coated with carbon coating comprising the at least one carbon material.

11. The process for producing composite particles according to any one of Claims 6 to 10, wherein oxidation treatment is used for the surface treatment of the at least one carbon material.

12. The process for producing composite particles according to any one of Claims 6 to 10, wherein a method using a surfactant is used for the surface treatment of the at least one carbon material.

13. The process for producing composite particles according to any one of Claims 6 to 10, wherein a method using a polymer dispersant is used for the surface treatment of the at least one carbon material.

14. Electrode material for a lithium-ion secondary battery, comprising 60 to 95% by mass of the composite particles according to any one of Claims 1 to 5 and the remainder consisting of an conduction aid and a binder.

15. A lithium-ion secondary battery comprising:

a positive electrode produced using the electrode material according to Claim 14;

a negative electrode;

an electrolytic solution; and

a separator that electrically insulates the positive electrode from the negative electrode and helps retain the electrolytic solution.

Abstract

Provided is positive electrode material for a highly safe lithium-ion secondary battery that can charge and discharge a large current while having long service life. Disclosed are composite particles comprising: particles of lithium-containing phosphate; and carbon coating comprising at least one carbon material selected from the group consisting of (i) fibrous carbon material, (ii) chain-like carbon material, and (iii) carbon material produced by linking together fibrous carbon material and chain-like carbon material, wherein each particle is coated with the carbon coating. The fibrous carbon material is preferably a carbon nanotube with an average fiber size of 5 to 200 nm. The chain-like carbon material is preferably carbon black produced by linking, like a chain, primary particles with an average particle size of 10 to 100 nm. The lithium-containing phosphate is preferably $LiFePO_4$, $LiMnPO_4$, $LiMn_XFe_{(1-X)}PO_4$, $LiCoPO_4$, or $Li_3V_2(PO_4)_3$.