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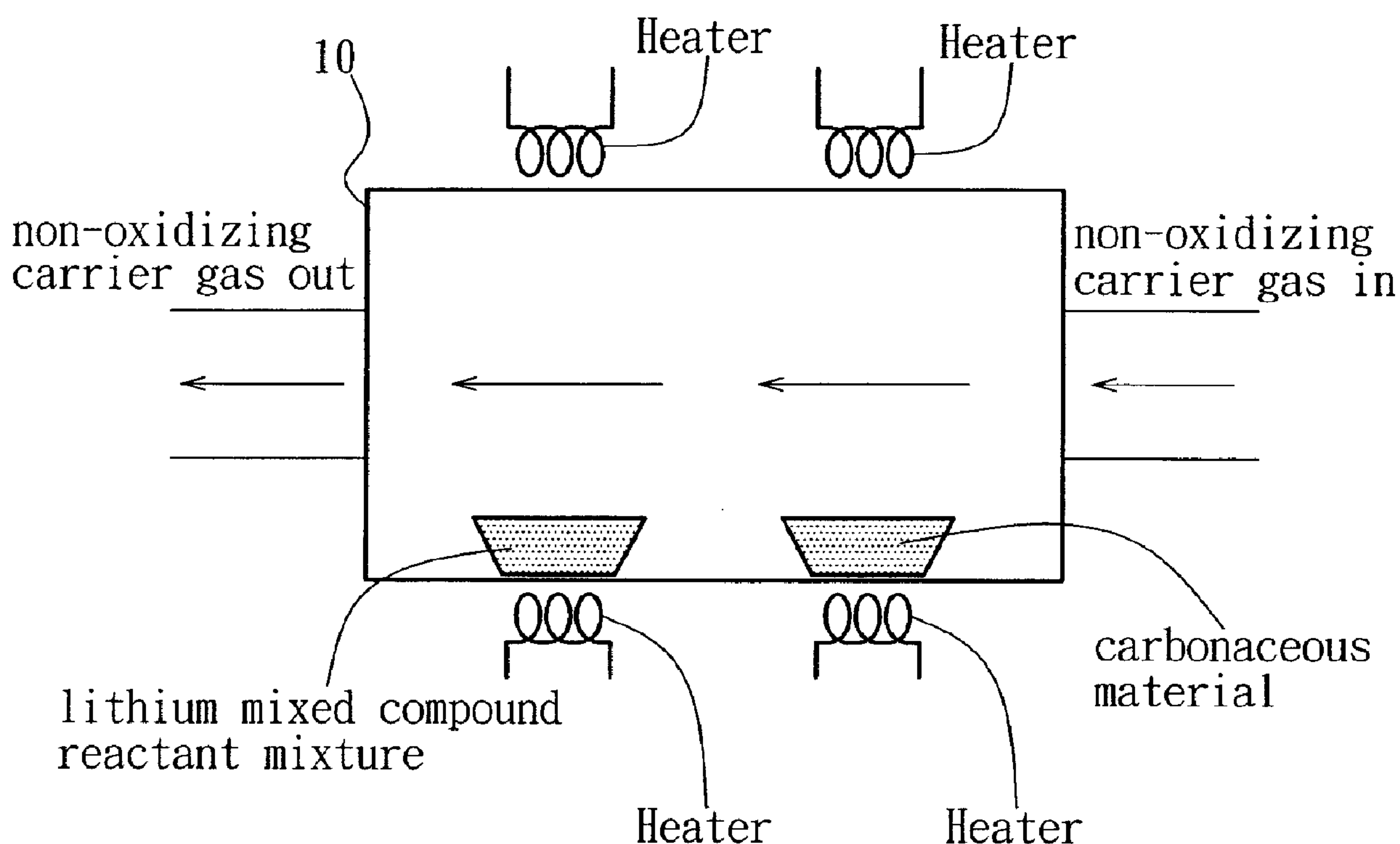
(72) Inventeur/Inventor:
YANG, CHIH-WEI, TW

(73) Propriétaire/Owner:
AQUIRE ENERGY CO., LTD., TW

(74) Agent: MARKS & CLERK

(54) Titre : METHODE POUR PRODUIRE UN COMPOSE METALLIQUE MIXTE COMPORTANT DU LITHIUM

(54) Title: METHOD FOR MAKING A LITHIUM MIXED METAL COMPOUND



(57) Abrégé/Abstract:

A method for making a lithium mixed metal compound includes: preparing a reactant mixture that contains a metal compound, a lithium compound, and optionally, a phosphate-containing compound; and exposing the reactant mixture to an atmosphere in the presence of suspended carbon particles, and conducting a reduction to reduce oxidation state of at least one metal ion of the reactant mixture at a temperature sufficient to form a reaction product containing lithium and the reduced metal ion.



ABSTRACT OF THE DISCLOSURE

A method for making a lithium mixed metal compound includes: preparing a reactant mixture that contains a metal compound, a lithium compound, and optionally, a phosphate-containing compound; and exposing the reactant mixture to an atmosphere in the presence of suspended carbon particles, and conducting a reduction to reduce oxidation state of at least one metal ion of the reactant mixture at a temperature sufficient to form a reaction product containing lithium and the reduced metal ion.

(Fig. 7)

METHOD FOR MAKING A LITHIUM MIXED METAL COMPOUND

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a method for making a lithium
5 mixed metal compound, more particularly to a method for
making a lithium mixed metal compound by exposing a reactant
mixture to an atmosphere in the presence of suspended carbon
particles.

2. Description of the Related Art

10 Lithium-containing transitional metal compounds,
such as layered cobalt compounds, layered nickel compounds
and spinel manganese compounds, have been developed for
use in cathode materials. However, the cobalt compounds,
such as lithium cobalt oxide (LiCoO_2), are hardly applied
15 to highly capacitive battery cells due to their
insufficient resources and poisonous properties. The
nickel compounds, such as lithium nickel oxide (LiNiO_2),
are difficult to synthesize and are unstable. In the past,
manganese compounds, such as lithium manganese oxide
20 (LiMn_2O_4), has been expected to be suitable for the high
capacity battery cells because they are usually perceived
to be economical and safe. However, they have been proved
to have low capacity and are unstable and poor in cycle
performance. In addition, when the cobalt compounds,
25 nickel compounds and manganese compounds are applied to
a battery cell, the initial capacity of the cell will
diminish during the first cycle operation and will further

decay obviously upon each subsequent cycle.

Another lithium-containing transitional metal compound, olivine lithium ferrous phosphate (LiFePO_4), has been considered for use in cathode materials. Being
5 excellent in environmental protection, and safety concerns, the lithium ferrous phosphate has good electrochemical properties, high specific capacity, exceptional cycle performance, and high thermal stability. Lithium ferrous phosphate has a slight twisted hexagonal close-packed
10 structure that includes a framework consisting of FeO_6 octahedrals, LiO_6 octahedrals, and PO_4 tetrahedrals. In the structure of lithium ferrous phosphate, one FeO_6 octahedral is co-sided with two LiO_6 octahedrals and one PO_4 tetrahedral. However, since the structure of such
15 lithium ferrous phosphate lacks continuous co-sided FeO_6 octahedral network, no free electrons can be formed to conduct electricity. In addition, since the PO_4 tetrahedrals restrict lattice volume change, insertion and extraction of the lithium ions in lithium ferrous
20 phosphate lattice is adversely affected, thereby significantly decreasing the diffusion rate of lithium ions. The conductivity and ion diffusion rate of lithium ferrous phosphate are decreased, accordingly.

Meanwhile, it has been generally agreed that the
25 smaller the particle size of the lithium ferrous phosphate, the shorter will be the diffusion path of the lithium ions, and the easier will be the insertion and extraction of

the lithium ions in lithium ferrous phosphate lattice, which is advantageous to enhance the ion diffusion rate. Besides, addition of conductive materials into the lithium ferrous phosphate is helpful in improving the conductivity of the lithium ferrous phosphate particles. Therefore, it has also been proposed heretofore to improve the conductivity of the lithium ferrous phosphate through mixing or synthesizing techniques.

Up to the present time, methods for synthesizing olivine lithium ferrous phosphate include solid state reaction, carbothermal reduction, and hydrothermal reaction. For example, U.S. Patent No. 5,910,382 discloses a method for synthesizing olivine compound LiFePO_4 powders by mixing stoichiometric proportions of Li_2CO_3 or $\text{LiOH}\cdot\text{H}_2\text{O}$, $\text{Fe}\{\text{CH}_2\text{COOH}\}_2$ and $\text{NH}_4\text{H}_2\text{PO}_4\cdot\text{H}_2\text{O}$, and heating the mixtures in an inert atmosphere at an elevated temperature ranging from 650°C to 800°C . However, the particle size of the resultant LiFePO_4 powders is relatively large with an uneven distribution, and is not suitable for charge/discharge under a large electrical current. In addition, the ferrous source, i.e. $\text{Fe}\{\text{CH}_2\text{COOH}\}_2$, is expensive, which results in an increase in the manufacturing costs, accordingly.

Furthermore, U.S. Patent Nos. 6,528,033, 6,716,372, and 6,730,281 disclose methods for making lithium-containing materials by combining an organic material and a mixture containing a lithium compound, a

ferric compound and a phosphate compound so that the mixture is mixed with excess quantities of carbon coming from the organic material and so that ferric ions in the mixture are reduced to ferrous ions. The mixture is subsequently
5 heated in a non-oxidizing inert atmosphere so as to prepare LiFePO_4 through carbothermal reduction. However, the methods provided by these prior art patents involve addition of a great amount of organic materials to the mixture, and excess quantities of carbon in LiFePO_4 tend
10 to reduce ferrous ions to iron metal and result in loss of specific capacity.

All the aforesaid methods for making LiFePO_4 involve solid-state reaction and require long reaction time and a high temperature treatment. The LiFePO_4 powders thus
15 formed have a relatively large particle size, a poor ionic conductivity, and a relatively high deteriorating rate in electrochemical properties. In addition, the LiFePO_4 powders thus formed are required to be ball-milled due to their large particle size, and the quality of the LiFePO_4
20 powders will deteriorate due to impurity interference.

In addition, the method for making LiFePO_4 through hydrothermal reaction may use soluble ferrous compound, lithium compound, and phosphoric acid as starting materials, so as to control the particle size of LiFePO_4 .
25 However, hydrothermal reaction is relatively difficult to carry out since it requires to be conducted at a high temperature and a high pressure.

Therefore, there is still a need to provide an economical and simple method for making a lithium mixed metal compound having a relatively small particle size and good conductivity.

5 **SUMMARY OF THE INVENTION**

Therefore, the objective of the present invention is to provide a method for making a lithium mixed metal compound that can alleviate the aforesaid drawbacks of the prior art.

10 According to one aspect of this invention, a method for making a lithium mixed metal compound includes: preparing a reactant mixture that comprises a metal compound and a lithium compound; and exposing the reactant mixture to an atmosphere in the presence of suspended carbon
15 particles, and conducting a reduction to reduce oxidation state of at least one metal ion of the reactant mixture at a temperature sufficient to form a reaction product comprising lithium and the reduced metal ion.

 According to another aspect of this invention, a method
20 for making a lithium mixed metal compound includes: preparing a reactant mixture that comprises a metal compound, a lithium compound, and a phosphate group-containing compound; and exposing the reactant mixture to an atmosphere in the presence of suspended carbon
25 particles, and conducting a reduction to reduce oxidation state of at least one metal ion of the reactant mixture at a temperature sufficient to form a single phase reaction

product comprising lithium, the reduced metal ion, and the phosphate group.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the present invention will become apparent in the following detailed description of the preferred embodiments of this invention, with reference to the accompanying drawings, in which:

Fig. 1 shows the results of an X-ray diffraction pattern of the LiFePO_4 powders prepared according to Example 1 of the present invention;

Fig. 2 shows the results of an X-ray diffraction pattern of the LiFePO_4 powders prepared according to Example 2 of the present invention;

Fig. 3 shows the results of an X-ray diffraction pattern of the LiFePO_4 powders prepared according to Example 6 of the present invention;

Fig. 4 shows a SEM photograph to illustrate surface morphology of the LiFePO_4 powders prepared according to Example 6 of the present invention;

Fig. 5 shows a specific capacity/cycle number plot of a battery cell with cathode material made from the LiFePO_4 powders prepared according to Example 6 of the present invention;

Fig. 6 shows a voltage/capacity plot of a battery cell with cathode material made from the LiFePO_4 powders prepared according to Example 6 of the present invention; and

Fig. 7 is a schematic view to illustrate how reduction of a metal ion of a reactant mixture is conducted in a reduction chamber in the first preferred embodiment of this invention.

5 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The first preferred embodiment of the method for making a lithium mixed metal compound includes: preparing a reactant mixture that includes a metal compound and a lithium compound; and exposing the reactant mixture to
10 an atmosphere in the presence of suspended carbon particles, and conducting a reduction to reduce oxidation state of at least one metal ion of the reactant mixture at a temperature sufficient to form a reaction product comprising lithium and the reduced metal ion.

15 Preferably, the reactant mixture is prepared by dissolving in water the metal compound and the lithium compound, and is subsequently dried prior to the reduction operation of the reactant mixture. More preferably, the reactant mixture is dried by oven-drying or spray-drying.
20 Most preferably, the reactant mixture is dried by oven-drying.

Referring to Fig. 7, the reduction operation of the reactant mixture is conducted in a reduction chamber 10. The atmosphere in the reduction chamber 10 is preferably
25 a non-oxidizing atmosphere that consists of a non-oxidizing carrier gas.

The suspended carbon particles may be formed by heating

a carbonaceous material in the reduction chamber 10 to form carbon particles that are subsequently suspended in the reduction chamber 10 by the non-oxidizing carrier gas introduced into the reduction chamber 10 to flow over the heated carbonaceous material. Preferably, the non-oxidizing carrier gas is inert or non-oxidizing to the reactant mixture, and is selected from the group consisting of nitrogen, argon, carbon monoxide carbon dioxide, and mixtures thereof. More preferably, the non-oxidizing carrier gas is nitrogen.

The carbonaceous material may be selected from the group consisting of charcoal, graphite, carbon powders, coal, organic compounds, and mixtures thereof. Preferably, the carbonaceous material is charcoal.

Additionally, the heating operation of the carbonaceous material in the reduction chamber 10 is conducted at a temperature higher than 300°C . Preferably, the carbonaceous material is heated at a temperature ranging from 300°C to 1100°C . More preferably, the carbonaceous material is heated at 700°C .

In the reactant mixture, the metal compound may be a compound of a metal selected from the group consisting of Fe, Ti, V, Cr, Mn, Co, Ni, and mixtures thereof. Preferably, the compound of the metal is one of ferric nitrate ($\text{Fe}(\text{NO}_3)_2$) and ferric chloride (FeCl_3), and the metal ion to be reduced in the reactant mixture is ferric ion (Fe^{3+}) or ferrous ion (Fe^{2+}).

Alternatively, the metal compound may be a combination of transitional metal powders made from a metal selected from the group consisting of Fe, Ti, V, Cr, Mn, Co, Ni, and mixtures thereof, and an acid. Preferably, the transitional metal powders are iron powders, and the metal ion to be reduced in the reactant mixture is ferric ion (Fe^{3+}) or ferrous ion (Fe^{2+}).

In addition, the aforesaid acid may be chosen from one of an inorganic acid and an organic acid. The inorganic acid may be selected from the group consisting of nitric acid (HNO_3), sulfuric acid (H_2SO_4), hydrochloric acid (HCl), perchloric acid (HClO_4), hypochloric acid (HClO_3), hydrofluoric acid (HF), hydrobromic acid (HBrO_3), phosphoric acid (H_3PO_4), and mixtures thereof. The organic acid may be selected from the group consisting of formic acid (HCOOH), acetic acid (CH_3COOH), propionic acid ($\text{C}_2\text{H}_5\text{COOH}$), citric acid ($\text{HOOCCH}_2\text{C}(\text{OH})(\text{COOH})\text{CH}_2\text{COOH}\cdot\text{H}_2\text{O}$), tartaric acid ($(\text{CH}(\text{OH})\text{COOH})_2$), lactic acid ($\text{CH}_3\text{CHOHCOOH}$), and mixtures thereof. Preferably, the acid is nitric acid or hydrochloric acid.

As for the lithium compound, it is preferably selected from the group consisting of lithium hydroxide (LiOH), lithium fluoride (LiF), lithium chloride (LiCl), lithium oxide (Li_2O), lithium nitrate (LiNO_3), lithium acetate (CH_3COOLi), lithium phosphate (Li_3PO_4), lithium hydrogen phosphate (Li_2HPO_4), lithium dihydrogen phosphate (LiH_2PO_4), lithium ammonium phosphate ($\text{Li}_2\text{NH}_4\text{PO}_4$), lithium

diammonium phosphate ($\text{Li}(\text{NH}_4)_2\text{PO}_4$), and mixtures thereof. More preferably, the lithium compound is lithium hydroxide.

5 Additionally, the reduction of the metal ion of the reactant mixture is conducted by heating the reactant mixture at a temperature ranging from 400°C to 1000°C for 1 to 30 hours. Preferably, the reduction of the metal ion is conducted at a temperature ranging from 450°C to 850°C for 4 to 20 hours. More preferably, the reduction of
10 the metal ion is conducted at about 700°C for 12 hours.

In addition, the first preferred embodiment of the method of this invention further includes adding a saccharide into the reaction mixture before the reduction operation of the reactant mixture. Preferably, the
15 saccharide is selected from the group consisting of sucrose, glycan, and polysaccharides. More preferably, the saccharide is sucrose.

The second preferred embodiment of the method for making a lithium mixed metal compound includes: preparing
20 a reactant mixture that comprises a metal compound, a lithium compound, and a phosphate group-containing compound; and exposing the reactant mixture to an atmosphere in the presence of suspended carbon particles, and conducting a reduction to reduce oxidation state of
25 at least one metal ion of the reactant mixture at a temperature sufficient to form a single phase reaction product comprising lithium, the reduced metal ion, and

the phosphate group.

In the second preferred embodiment, the preferred species of the lithium compound and the metal compound, process for forming the suspended carbon particles, and the operating conditions for the exposing and reduction operations of the reactant mixture are similar to those of the first preferred embodiment and have been explained hereinabove in detail.

As for the reactant mixture of the second preferred embodiment, it is preferably formed by preparing a solution comprising the metal ion dissociated from the metal compound, Li^+ dissociated from the lithium compound, and $(\text{PO}_4)^{3-}$ dissociated from the phosphate group-containing compound, followed by drying the solution. The single phase reaction product thus formed has a formula of $\text{Li}_x\text{M}_y\text{PO}_4$, in which $0.8 \leq x \leq 1.2$, and $0.8 \leq y \leq 1.2$. M represents a metal of the reduced metal ion, and is selected from the group consisting of Fe, Ti, V, Cr, Mn, Co, Ni, and combinations thereof.

Preferably, the phosphate group-containing compound is selected from the group consisting of ammonium hydrogen phosphate $((\text{NH}_4)_2\text{HPO}_4)$, ammonium dihydrogen phosphate $((\text{NH}_4)\text{H}_2\text{PO}_4)$, ammonium phosphate $((\text{NH}_4)_3\text{PO}_4)$, phosphorus pentoxide (P_2O_5) , phosphoric acid (H_3PO_4) , lithium phosphate (Li_3PO_4) , lithium hydrogen phosphate $(\text{Li}_2\text{HPO}_4)$, lithium dihydrogen phosphate $(\text{LiH}_2\text{PO}_4)$, lithium ammonium phosphate $(\text{Li}_2\text{NH}_4\text{PO}_4)$, lithium diammonium phosphate

($\text{Li}(\text{NH}_4)_2\text{PO}_4$), and mixtures thereof. More preferably, the phosphate group-containing compound is phosphoric acid (H_3PO_4).

Examples

5 Reactants and equipments:

1. Ferric nitrate (FeNO_3): commercially obtained from C-Solution Inc., Taiwan;
2. Ferric chloride (FeCl): commercially obtained from C-Solution Inc., Taiwan;
- 10 3. Iron powders: Hoganas Ltd., Taiwan, mode no. NC-100.24;
4. Nitrogen gas (N_2): commercially obtained from C-Solution Inc., Taiwan;
5. Nitric acid (HNO_3): commercially obtained from C-Solution Inc., Taiwan;
- 15 6. Hydrochloric acid (HCl): commercially obtained from C-Solution Inc., Taiwan;
7. Phosphoric acid (H_3PO_3): commercially obtained from C-Solution Inc., Taiwan;
8. Lithium hydroxide (LiOH): Chung-Yuan Chemicals,
20 Taiwan;
9. Sucrose: commercially obtained from Taiwan Sugar Corporation, Taiwan;
10. Carbon black: commercially obtained from Pacific Energytech Co., Ltd., Taiwan;
- 25 11. Polyvinylidene difluoride (PVDF): commercially obtained from Pacific Energytech Co., Ltd., Taiwan;
and

12. Tubular furnace: commercially obtained from Ultra Fine Technologies, Inc., Taiwan.

Example 1

0.2 mole of FeNO_3 was added to 200 ml of deionized water.
5 After the FeNO_3 was completely dissolved in the deionized water, 100 ml of 2N LiOH solution was then added, so as to form a reactant mixture having a stoichiometric ratio 1:1:1 of $\text{Fe}^{3+}:\text{Li}^+:\text{PO}_4^{3-}$. The reactant mixture was dried into a powder form, and was then placed in an aluminum oxide
10 crucible. The crucible together with charcoal was placed in a tubular furnace which was heated at 700°C for 12 hours in the presence of an argon carrier gas charging into the furnace. Carbon particles formed from the charcoal were suspended in the argon carrier gas and were mixed with
15 the reactant mixture. A single phase LiFePO_4 powder product, containing the carbon particles and LiFePO_4 powders, was obtained.

The LiFePO_4 powder product thus formed was analyzed by $\text{CuK}\alpha$ X-ray diffraction analyzer (manufactured by SGS
20 Taiwan Ltd., Taiwan) and the results are shown in Fig. 1. The X-ray pattern shown in Fig. 1 demonstrates that the LiFePO_4 powders in the LiFePO_4 powder product have an olivine crystal structure.

Example 2

25 In this example, LiFePO_4 powder product, containing the carbon particles and LiFePO_4 powders, was prepared in a manner similar to that of Example 1, except that 0.2

mole of FeNO_3 was replaced with 0.2 mole of FeCl_3 .

The LiFePO_4 powder product thus formed was analyzed by $\text{CuK}\alpha$ X-ray diffraction analyzer, and the results are shown in Fig. 2. The X-ray pattern shown in Fig. 2 demonstrates that the LiFePO_4 powders in the LiFePO_4 powder product have an olivine crystal structure.

Example 3

In this example, LiFePO_4 powder product, containing the carbon particles and LiFePO_4 powders, was prepared in a manner similar to that of Example 1, except that 0.2 mole of FeNO_3 was replaced with a mixture of 0.2 mole of iron powders and 50 ml of concentrated HNO_3 .

Example 4

In this example, LiFePO_4 powder product, containing the carbon particles and LiFePO_4 powders, was prepared in a manner similar to that of Example 3, except that 50 ml of concentrated HNO_3 was replaced with 100 ml of concentrated HCl .

Example 5

In this example, LiFePO_4 powder product, containing the carbon particles and LiFePO_4 powders, was prepared in a manner similar to that of Example 3, except that 50 ml of concentrated HNO_3 was replaced with 0.2 mole of H_3PO_4 .

Example 6

In this example, LiFePO_4 powder product, containing the carbon particles and LiFePO_4 powders, was prepared in a manner similar to that of Example 5, except that 3.2

g of sucrose was added to the reactant mixture before the reactant mixture was dried and heated.

The LiFePO_4 powder product thus formed was analyzed by $\text{CuK}\alpha$ X-ray diffraction analyzer and observed by scanning electron microscope (SEM), and the results are shown in Figs. 3 and 4, respectively. The X-ray pattern shown in Fig. 3 and the photograph shown in Fig. 4 demonstrate that the LiFePO_4 powders in the LiFePO_4 powder product have an olivine crystal structure and a particle size of about 100 nm.

Example 7

A mixture containing the LiFePO_4 powder product obtained from Example 6, carbon black, and polyvinylidene difluoride (PVDF) in a ratio of 83:10:7 was prepared and mixed thoroughly. The mixture was subsequently coated on a piece of aluminum foil and was dried to form a cathode. The cathode was applied to a battery cell, and the battery cell was subjected to a charge/discharge test in a charge/discharge tester. The battery cell was charged and discharged at an approximate C/5 (5 hour) rate at a voltage ranging from 2.5 V and 4.5 V. The results of specific capacity variation are shown in Fig. 5. The results of voltage variation at the charge and discharge plateau in the 15th cycle at room temperature are shown in Fig. 6. According to the results shown in Fig. 5, the initial specific capacity of the battery cell at room temperature is about 148 mAh/g, while after thirty cycles of

charge/discharge operations, the specific capacity of the battery cell at room temperature reaches about 151 mAh/g. These results demonstrate that the battery cell has a good cycle stability. According to the results shown in Fig. 6, the charge/discharge performance and stability are improved.

In view of the foregoing, high temperature and pressure operations utilized in the conventional methods are not required in the method of this invention. Besides, compared with the LiFePO_4 powder product obtained from the conventional methods, the LiFePO_4 powders in the LiFePO_4 powder product obtained according to the method of the present invention have a smaller particle size and more uniform particle size distribution, and the ball-milling treatment required in the conventional method can be omitted. Therefore, the method of this invention is more economical than the conventional methods in terms of production cost. Additionally, the LiFePO_4 powder product obtained according to the method of the present invention is a mixture of the LiFePO_4 powders and carbon particles, and the presence of the carbon particles can enhance the electrical conductivity of the LiFePO_4 powders.

While the present invention has been described in connection with what is considered the most practical and preferred embodiments, it is understood that this invention is not limited to the disclosed embodiments but is intended to cover various arrangements included within

the spirit and scope of the broadest interpretation and equivalent arrangements.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method for making a lithium mixed metal compound comprising:

preparing a reactant mixture that comprises a metal compound and a lithium compound; and

attaching carbon particles to the reactant mixture by passing suspended carbon particles, which are carried by a non-oxidizing carrier gas, therethrough, and reducing the oxidation state of at least one metal ion of the reactant mixture through the carbon particles attached to the reactant mixture.

2. The method of claim 1, wherein the reduction operation of the reactant mixture is conducted in a reduction chamber, and wherein the suspended carbon particles carried by the non-oxidizing carrier gas are formed by heating a carbonaceous material in the reduction chamber to form carbon particles which are subsequently suspended in the reduction chamber by the non-oxidizing carrier gas introduced into the reduction chamber to flow over the heated carbonaceous material.

3. The method of claim 2, wherein the non-oxidizing carrier gas is nitrogen, argon, carbon monoxide, or carbon dioxide, or any mixture thereof.

4. The method of any one of claims 1 to 3, wherein the reduction of the metal ion of the reactant mixture is conducted at a temperature ranging from 400°C to 1000°C for 1 to 30 hours.

5. A method for making a lithium mixed metal compound comprising:

preparing a reactant mixture that comprises a metal compound, a lithium compound, and a phosphate group-containing compound; and

attaching carbon particles to the reactant mixture by passing suspended carbon particles, which are carried by a non-oxidizing carrier gas, therethrough, and reducing the oxidation state of at least one metal ion of the reactant mixture through the carbon particles attached to the reactant mixture to form a single phase reaction product comprising lithium, the reduced metal ion, and the phosphate group.

6. The method of claim 5, wherein the reactant mixture is formed by preparing a solution that comprises the metal ion dissociated from the metal compound, Li^+ dissociated from the lithium compound, and $(\text{PO}_4)^{3-}$ dissociated from the phosphate group-containing compound, followed by drying the solution,

the single phase reaction product having a formula of $\text{Li}_x\text{M}_y\text{PO}_4$, in which $0.8 \leq x \leq 1.2$, $0.8 \leq y \leq 1.2$, and M represents the reduced metal ion and is Fe, Ti, V, Cr, Mn, Co, or Ni, or any combination thereof.

7. The method of claim 5 or 6, wherein the reduction operation of the reactant mixture is conducted in a reduction chamber, and wherein the suspended carbon particles carried by the non-oxidizing carrier gas are formed by heating a carbonaceous material in a reduction chamber to form carbon particles which are subsequently suspended in the reduction chamber by the non-oxidizing

carrier gas introduced into the reduction chamber to flow over the heated carbonaceous material.

8. The method of claim 7, wherein the non-oxidizing carrier gas is nitrogen, argon, carbon monoxide, or carbon dioxide, or any mixture thereof.

9. The method of claim 7 or 8, wherein the carbonaceous material is charcoal, graphite, a carbon powder, coal, or an organic compound, or any mixture thereof.

10. The method of any one of claims 7 to 9, wherein the heating operation of the carbonaceous material is conducted at a temperature ranging from 300°C to 1100°C.

11. The method of any one of claims 5 to 10, wherein the metal compound is formed from a mixture of transition metal powders and an acid.

12. The method of claim 11, wherein the acid is an inorganic acid consisting of nitric acid, sulfuric acid, hydrochloric acid, perchloric acid, hypochloric acid, hydrofluoric acid, hydrobromic acid, or phosphoric acid, or any mixture thereof.

13. The method of claim 11, wherein the acid is an organic acid consisting of formic acid, acetic acid, propionic acid, citric acid, tartaric acid, or lactic acid, or any mixture thereof.

14. The method of any one of claims 11 to 13, wherein the transition metal powders are iron powders.

15. The method of claim 14, wherein the metal compound is ferric nitrate or ferric chloride.

16. The method of any one of claims 5 to 15, wherein the lithium compound is lithium hydroxide, lithium fluoride, lithium chloride, lithium oxide, lithium nitrate, lithium acetate, lithium phosphate, lithium hydrogen phosphate, lithium dihydrogen phosphate, lithium ammonium phosphate, or lithium diammonium phosphate, or any mixture thereof.

17. The method of any one of claims 5 to 16, wherein the phosphate group-containing compound is ammonium hydrogen phosphate, ammonium dihydrogen phosphate, ammonium phosphate, phosphorus pentoxide, phosphoric acid, lithium phosphate, lithium hydrogen phosphate, lithium dihydrogen phosphate, lithium ammonium phosphate, or lithium diammonium phosphate, or any mixture thereof.

18. The method of any one of claims 5 to 17, further comprising the addition of a saccharide into the reactant mixture before the reduction operation of the reactant mixture.

19. The method of claim 18, wherein the saccharide is sucrose, glycan, or a polysaccharide.

20. The method of any one of claims 5 to 19, wherein the reduction of the metal ion of the reactant mixture is conducted at a temperature ranging from 400°C to 1000°C for 1 to 30 hours.

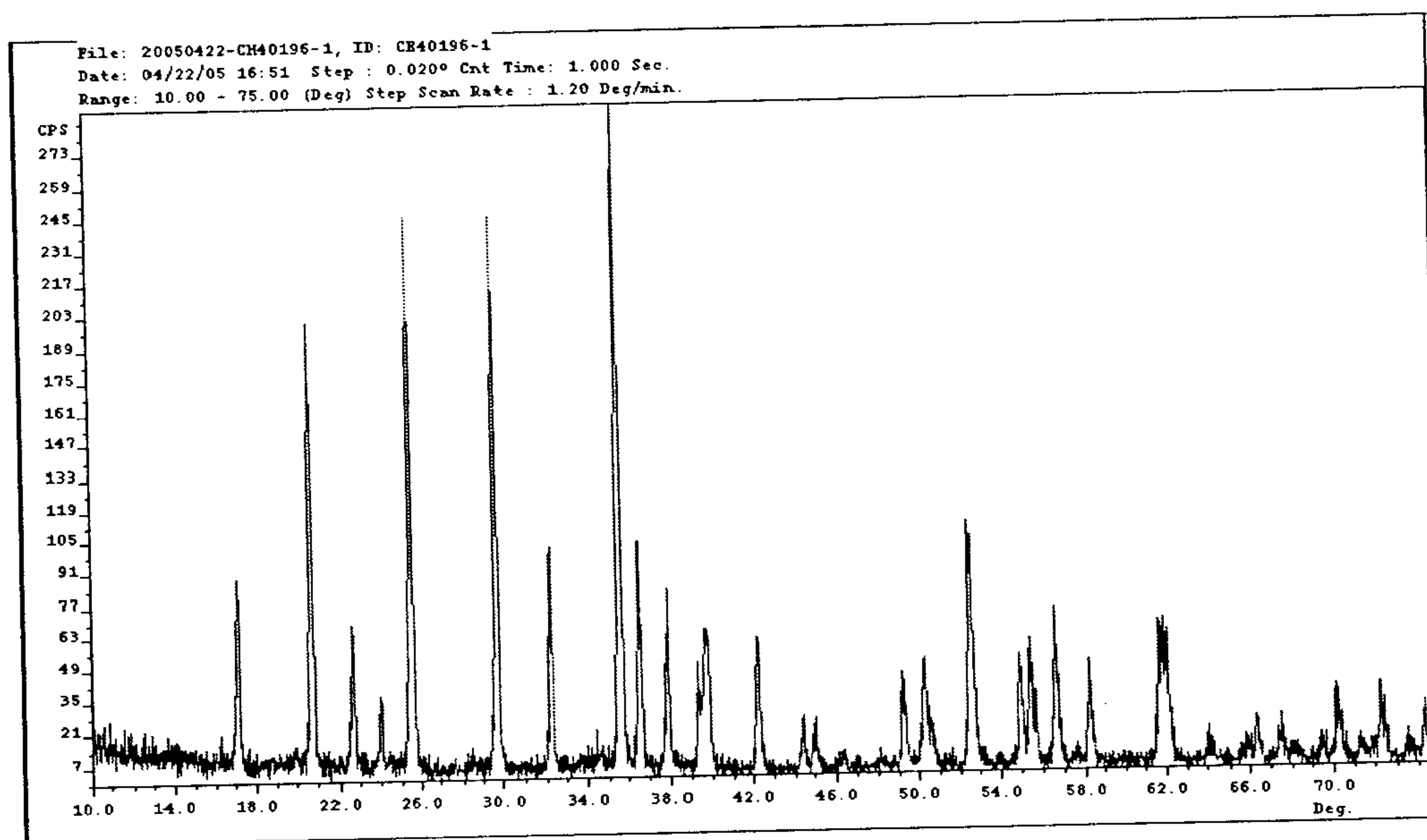


FIG.1

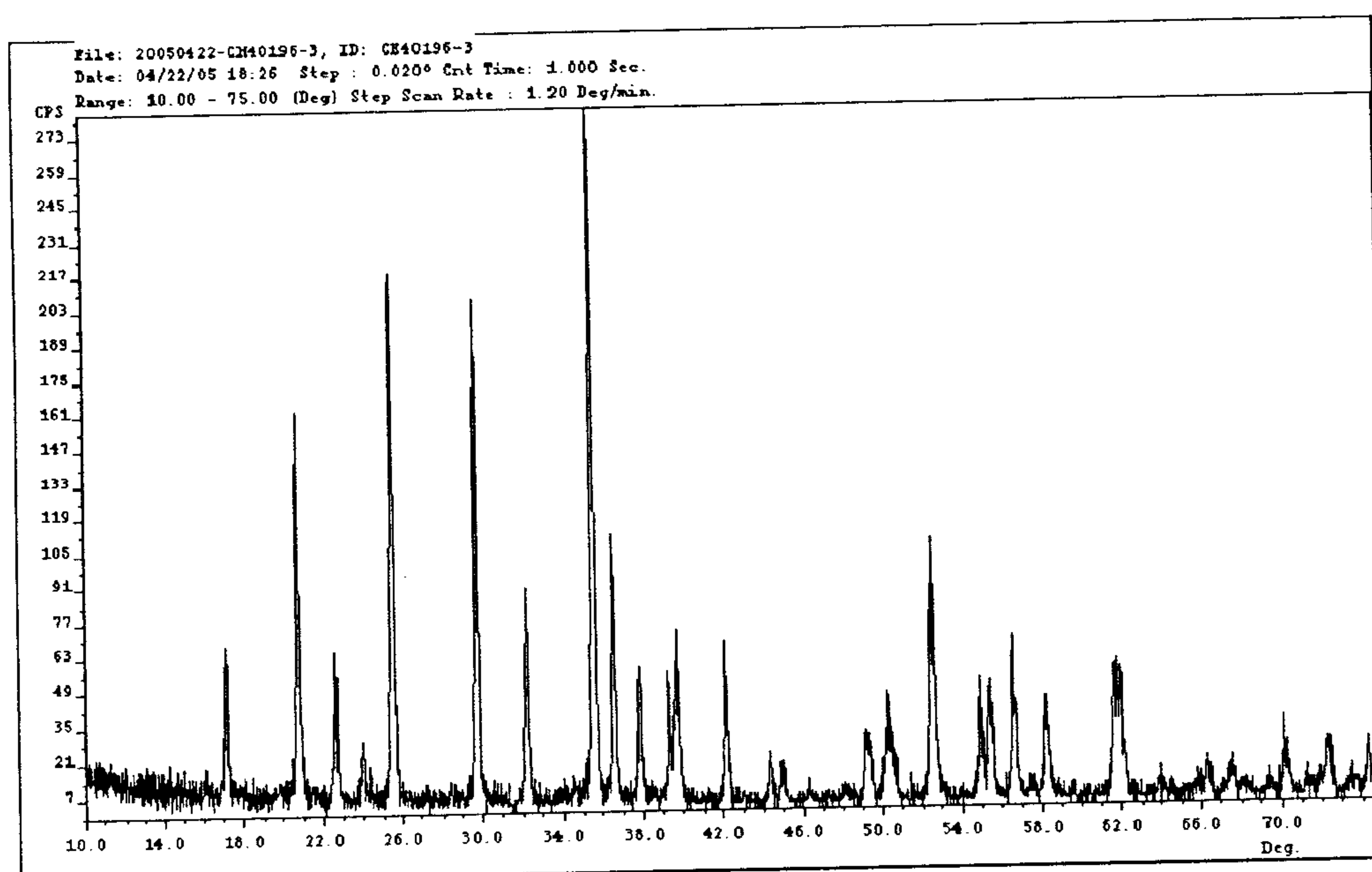


FIG.2

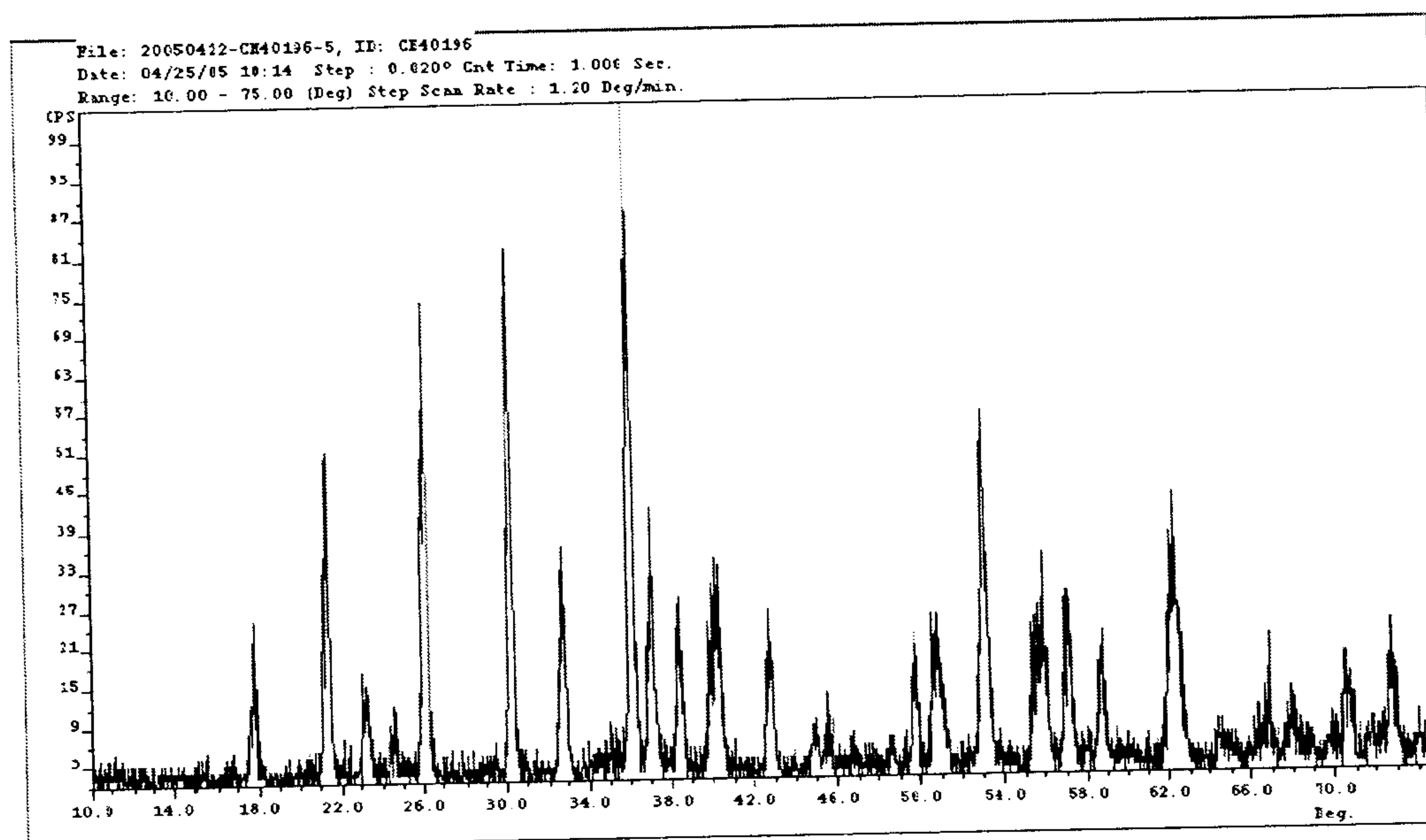


FIG.3

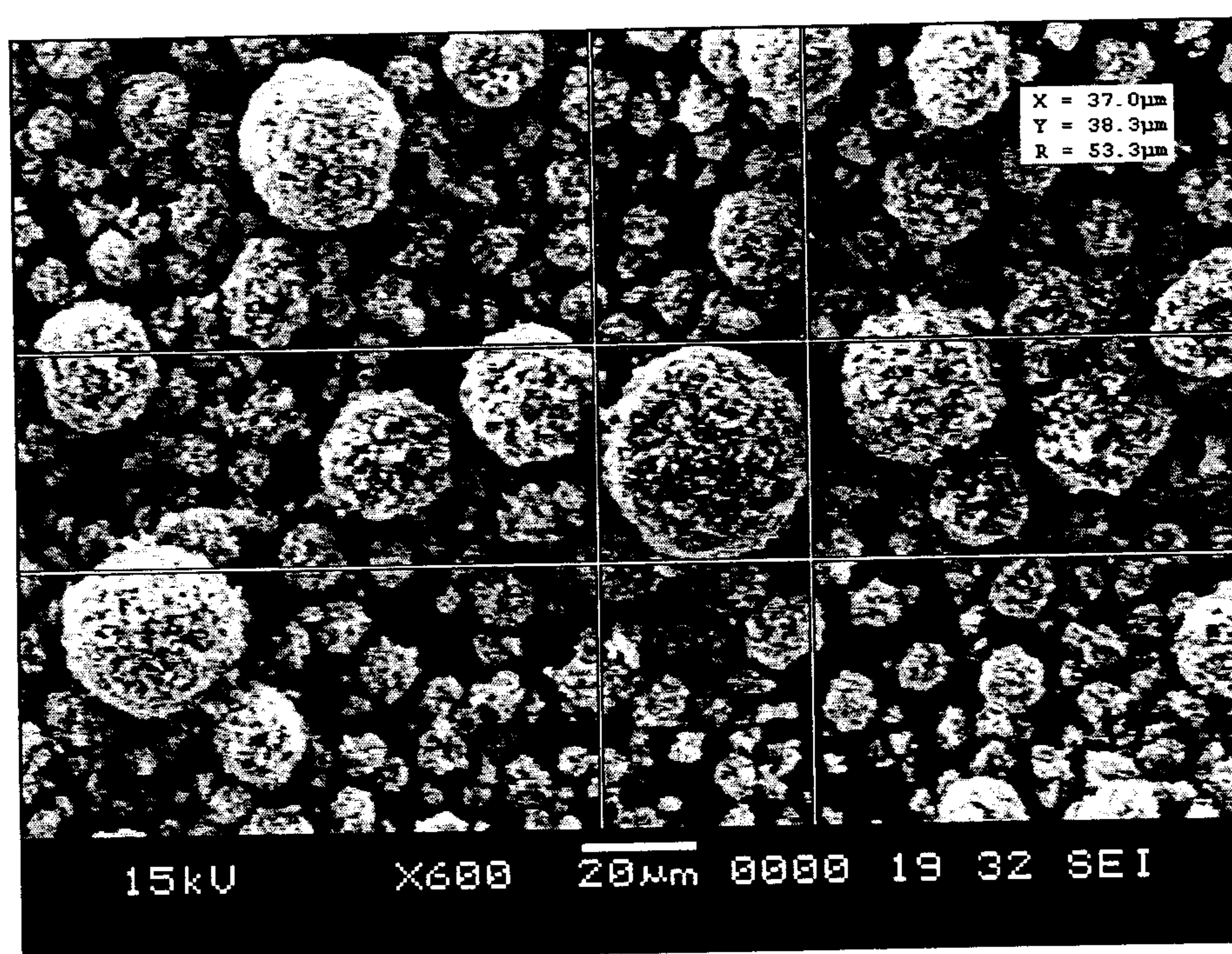


FIG.4

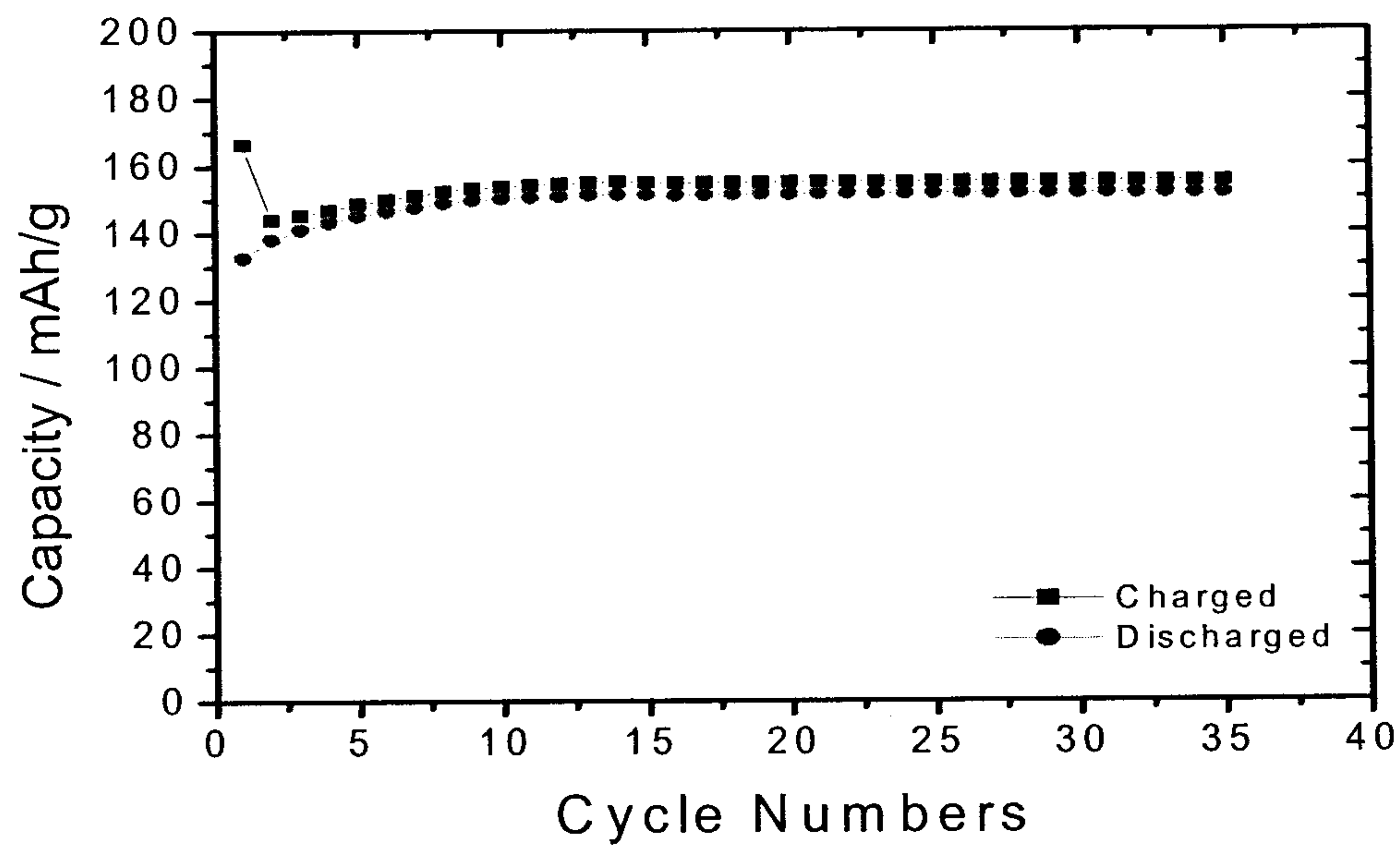


FIG. 5

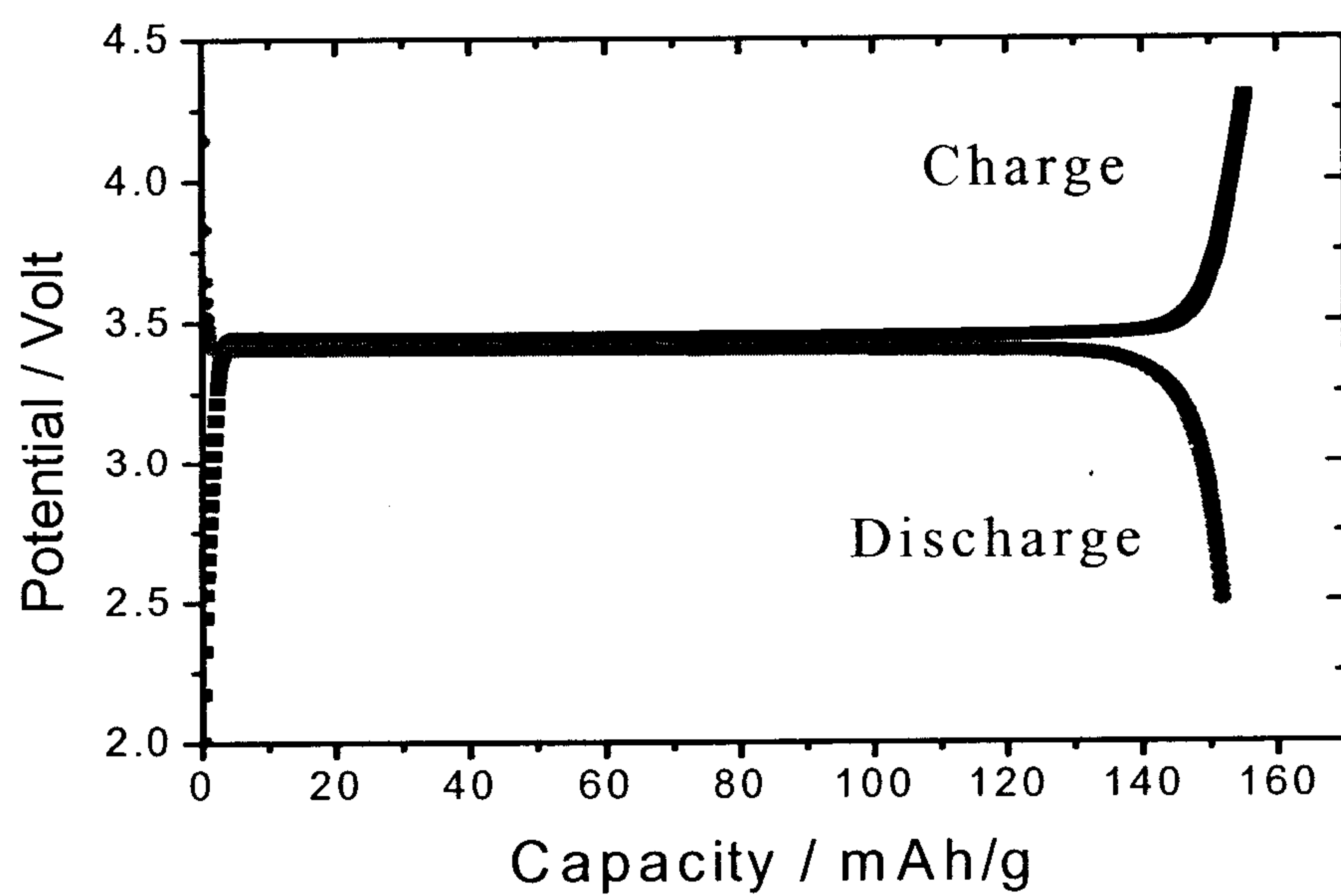


FIG. 6

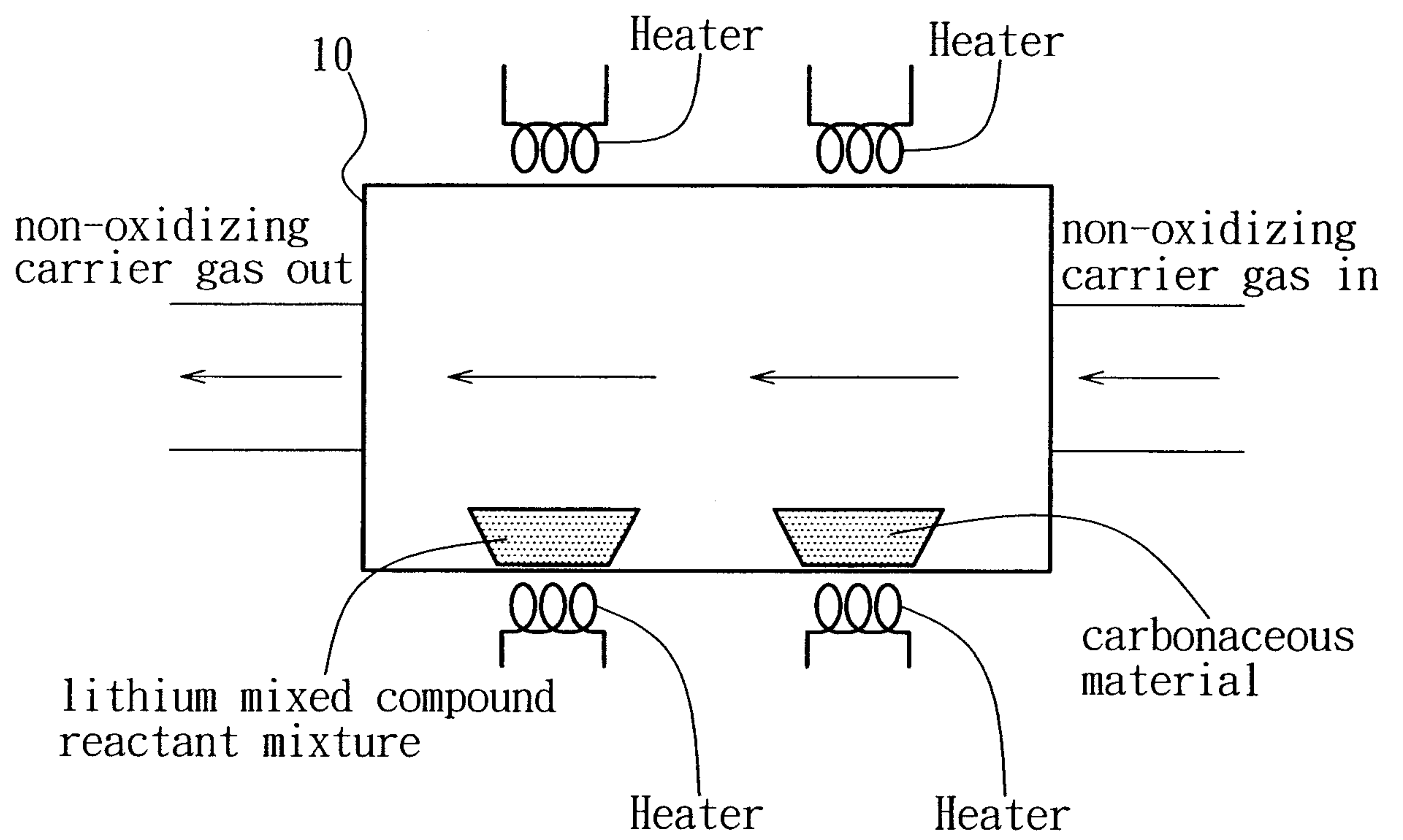


FIG. 7

