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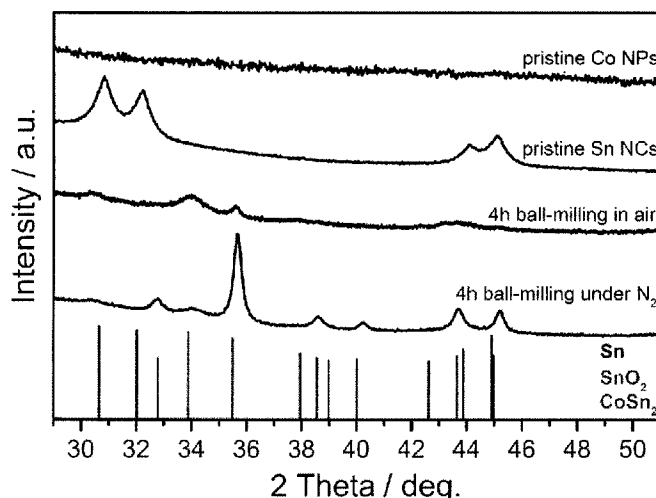
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(54) Titre : METHODE DE PRODUCTION DE NANOPARTICULES MSn_x COMME MATERIAUX D'ANODE POUR UNE BATTERIE RECHARGEABLE

(54) Title: METHOD FOR THE PRODUCTION OF MSn_x NANOPARTICLES AS ANODE MATERIALS FOR A RECHARGEABLE BATTERY



(57) Abrégé/Abstract:

The invention relates to a method for the production of MSn_x nanoparticles, wherein M is an element selected from the group consisting of Co, Mn, Fe, Ni, Cu, In, Al, Ge, Pb, Bi, Ga, and $0 < x \leq 10$ said method comprising the steps of: - synthesizing Sn nanoparticles by reducing a tin salt with a solution of a hydride in an anhydrous polar solvent, separating the solid Sn nanoparticles formed from the solution, and washing the Sn nanoparticles, - synthesizing M nanoparticles by reducing a metal salt with a solution of a hydride in an anhydrous polar solvent, separating the solid M nanoparticles formed from the solution, and washing the M nanoparticles, - mechanical mixing said Sn nanoparticles and said M nanoparticles to convert them into MSn_x nanoparticles.

ABSTRACT

The invention relates to a method for the production of MSn_x nanoparticles, wherein

M is an element selected from the group consisting of Co, Mn,
5 Fe, Ni, Cu, In, Al, Ge, Pb, Bi, Ga, and

$$0 < x \leq 10$$

said method comprising the steps of:

- 10 - synthesizing Sn nanoparticles by reducing a tin salt with a solution of a hydride in an anhydrous polar solvent, separating the solid Sn nanoparticles formed from the solution, and washing the Sn nanoparticles,
- 15 - synthesizing M nanoparticles by reducing a metal salt with a solution of a hydride in an anhydrous polar solvent, separating the solid M nanoparticles formed from the solution, and washing the M nanoparticles,
- mechanical mixing said Sn nanoparticles and said M nanoparticles to convert them into MSn_x nanoparticles.

Method for the production of MSn_x nanoparticles as anode materials for a rechargeable battery

Field of the invention

The present invention generally relates to a method for the production
5 of MSn_x nanoparticles as anode materials for a rechargeable battery, in particular a sodium-ion or a lithium-ion battery, and to a method for producing an anode comprising such materials.

Background of the invention

Despite extensive research on materials for rechargeable Lithium-ion
10 batteries in the last decades, graphite is still the most widely used anode material for commercial cells. However, graphite has a relatively low specific and volumetric capacity (372 mAhg^{-1} ; 820 mAhcm^{-3}) compared to many alloying (e.g. Si, Ge, Sn) and conversion-type materials (e.g. Fe_3O_4 , MoS_2 , SnSb). Although these materials suffer commonly from massive volume
15 changes occurring during lithiation/delithiation, it has been demonstrated for a multitude of systems that this issue can be mitigated by using nanostructured materials.[1] Nevertheless, commercialization of such high-capacity alloying or conversion-type anodes has been hampered for several reasons. Especially for conversion-type anodes, often a major fraction of the
20 capacity is obtained at potentials beyond 1.0 V vs. Li^+/Li , resulting in low energy densities for the corresponding full-cells. Secondly, often synthesis of battery materials is too cost-intensive or too complicated to be implemented on the industrial scale. Among the few materials, which are realistic candidates to replace graphite in commercial cells is Sn, because it combines
25 most of the crucial properties: high volumetric and specific capacities ($\sim 7300 \text{ mAhcm}^{-3}$, 992 mAhg^{-1}), low delithiation potential, high electric conductivity and reasonable price. In fact, anodes based on an amorphous Sn-Co-C nanocomposite are currently being used in Sony's Nexelion™

battery which has triggered intensive research on Co-Sn based anodes for Lithium-ion batteries.[2]

Therefore, suitable materials to replace graphite as anode are urgently needed in order to improve the energy density of rechargeable battery, in particular Lithium-ion batteries, for increasingly important applications such as portable electronics or electric cars.

It is therefore necessary to develop a cheap and simple procedure that allows the production of MSn_x nanoparticles showing high electrochemical performance as anode materials for rechargeable battery, in particular Lithium-ion batteries.

Disclosure of the Invention

Hence, it is a general object of the invention to provide a method for the production of MSn_x nanoparticles, wherein

M is an element selected from the group consisting of Co, Mn, Fe, Ni, Cu, In, Al, Ge, Pb, Bi, Ga, and

$0 < x \leq 10$, and preferably $0 < x \leq 3$

According to the invention, the method for the production of MSn_x nanoparticles comprises the steps of:

- synthesizing Sn nanoparticles by reducing a tin salt with a solution of a hydride in an anhydrous polar solvent, separating the solid Sn nanoparticles formed from the solution, and washing the Sn nanoparticles,
- synthesizing M nanoparticles by reducing a metal salt with a solution of a hydride in an anhydrous polar solvent, separating the solid M nanoparticles formed from the solution, and washing the M nanoparticles,
- mechanical mixing said Sn nanoparticles and said M nanoparticles to convert them into nanoalloys of MSn_x nanoparticles.

It is a further object of the invention to provide a method for producing an anode for rechargeable battery, in particular Sodium-ion or Lithium-ion batteries, said anode comprising a tin based material obtained by the method of the present invention.

5 Preferably, the molar ratio (M/Sn) of M nanoparticles and Sn nanoparticles for the mechanical mixing step may be comprised between 1:1 and 1:3.

Advantageously, the mechanical mixing may be obtained by ball-milling which may be performed in air or in inert gas, for example under
10 nitrogen. Preferably, the ball-milling is performed in air.

In some preferred embodiments M is Co, and x may be preferably about 2.

The reduction reaction of the tin salt is preferably performed at elevated reaction temperature such as at a temperature comprised between
15 50°C and 70°C.

The reduction reaction of the metal salt is preferably performed at more elevated reaction temperature such as at a temperature comprised between 60°C and 180°C, depending on the reactivity of the metal salt.

Examples for suitable hydrides are NaBH₄, lithium hydride, sodium
20 hydride, potassium hydride, magnesium hydride, calcium hydride, tributyltinhydride, diisobutyl aluminum hydride, lithium aluminum hydride, lithium triethylborohydride and mixtures thereof. A preferred hydride is NaBH₄.

Examples for anhydrous polar solvents are 1-methyl-2-pyrrolidone
25 (NMP), hexamethylphosphoramide, 1,3-dimethyl-2-imidazolidinone, 1,3-dimethyl-3,4,5,6-tetrahydro-2(1H)-pyrimidinone, linear ether such as glyme, diglyme, triethylene glycol dimethylether but not limited thereto, sulfoxide such as dimethylsulfoxide or sulfolane but not limited thereto, and mixtures thereof. A preferred anhydrous polar solvent is NMP.

Examples for suitable tin salts are tin chloride, tin fluoride, tin bromide, tin iodide, tin oxide, tin sulfide, sodium stannate trihydrate, tetrabutyltin, and mixtures thereof, preferably tin chloride.

5 Examples for suitable alloying metal salts are M chlorides (MCl_2), M fluorides, M bromides, M iodides, M oxides, M sulfides, M sulfates and mixtures thereof, preferably mixtures of Co salts, and most preferably Co chloride ($CoCl_2$).

10 The reduction reaction of the tin salt or of the metal salt respectively may be performed in inert gas, preferably under nitrogen or may also be performed in air.

In a preferred method, the step of synthesizing the Sn nanoparticles may comprise the steps of:

- preparing a solution of hydride in anhydrous solvent and at least one solution of tin salt in anhydrous solvent,
- 15 - heating the solution of hydride to the reaction temperature of the reduction reaction of the tin salt, and
- starting the reduction reaction when the reaction temperature of the reduction reaction of the tin salt is reached by quick injection of the one or more tin salt solutions into the solution of hydride to generate
- 20 a reaction mixture. Quick means that addition was performed with highest possible speed and without interruption. In the reaction mixture, Sn nanoparticles are generated by adding the one or more tin salt to the hydride, and are formed instantaneously.

25 In another embodiment, the step of synthesizing the Sn nanoparticles may comprise the steps of:

- preparing a solution of one or more tin salts in anhydrous solvent and at least one solution of hydride in anhydrous solvent,
- heating the solution of tin salts to the reaction temperature of the reduction reaction of the tin salt, and

5 - starting the reduction reaction when the reaction temperature of the reduction reaction of the tin salt is reached by quick injection of the hydride solution into the solution of one or more tin salts to generate a reaction mixture in which Sn nanoparticles are formed instantaneously.

In a preferred method, the step of synthesizing the M nanoparticles may comprise the steps of:

- preparing a solution of hydride in anhydrous solvent and at least one solution of metal salt in anhydrous solvent,
- 10 - heating the solution of hydride to the reaction temperature of the reduction reaction of the metal salt, and
- 15 - starting the reduction reaction when the reaction temperature of the reduction reaction of the metal salt is reached by quick injection of the one or more metal salt solutions into the solution of hydride to generate a reaction mixture. Quick means that addition was performed with highest possible speed and without interruption. In the reaction mixture, M nanoparticles are generated by adding the one or more metal salt to the hydride, and are formed instantaneously.

20 In another embodiment the step of synthesizing the M nanoparticles may comprise the steps of:

- preparing a solution of one or more metal salts in anhydrous solvent and at least one solution of hydride in anhydrous solvent,
- heating the solution of metal salts to the reaction temperature of the reduction reaction of the metal salt, and
- 25 - starting the reduction reaction when the reaction temperature of the reduction reaction of the metal salt is reached by quick injection of the hydride solution into the solution of one or more metal salts to generate a reaction mixture in which M nanoparticles are formed instantaneously.

Advantageously, the reaction mixture, which has been generated during one of the syntheses described above, is cooled to room temperature immediately after injection. More particularly, in a preferred embodiment the reaction mixture formed by combining the tin salt solution or the metal salt solution respectively with the hydride solution is cooled to room temperature immediately after injection of the one or more tin salt solutions or of the one or more metal salt solutions respectively, by using for example a water-ice bath.

Preferably, the solid Sn nanoparticles or the M nanoparticles which are formed are separated from their respective reaction mixture by centrifugation.

Then the obtained solid Sn nanoparticles or the M nanoparticles are respectively washed preferably first with a solvent as dimethyl sulfoxide (DMSO) and then with water.

Prior to mechanical mixing, the Sn or M nanoparticles may be dried in a vacuum oven at room temperature.

The method of the invention uses simple preparative procedures based on inexpensive precursors for synthesizing M-Sn based nanoparticles combining wet-chemical synthesis and mechanical ball-milling.

An anode may be prepared by mixing the MSn_x nanoparticles obtained as described above, carbon black, carboxy methyl cellulose (CMC) and water. The aqueous slurry obtained is then coated on a current collector and subsequently dried prior to battery assembly.

Using such an anode, a Lithium-ion battery or a Sodium-ion battery may be produced according to procedures well known in the art.

Brief Description of the Drawings

The invention will be better understood and objects other than those set forth above will become apparent when consideration is given to the following detailed description thereof. This description makes reference to the annexed drawings which show:

Figure 1. X-ray diffraction (XRD) patterns of Co NPs, Sn NCs, CoSn_x NPs prepared by ball-milling in air and CoSn₂ NCs prepared by ball-milling under nitrogen atmosphere by the method of the invention

Figure 2. EDX-spectrum of amorphous Co NPs

Figure 3. Transmission electron microscopy (TEM) images of Co NPs (A), Sn NCs (B), CoSn_x NPs (C) and CoSn₂ NCs (D)

Figure 4. Capacity retention for Sn NCs, CoSn₂ NCs and CoSn_x NPs in lithium-ion half-cells at a current of 1984 mA_g⁻¹ within the potential range 0.005-1.0 V

Figure 5. Galvanic charge/discharge curves for Sn NCs (A), CoSn₂ NCs (B) and CoSn_x NPs (C) corresponding to Figure 4.

Figure 6. Cyclic voltammogram of Sn NCs (A), CoSn₂ NCs (B) and CoSn_x NPs (C) tested in a lithium-ion half-cell using a scan rate of 0.1 Vs⁻¹ in the potential range 0.005-1.0 V

Figure 7. Rate capability measurements for Sn NCs, CoSn₂ NCs and CoSn_x NPs in Lithium-ion half-cells within the potential range 0.005-1.0 V

Figure 8. (A) Capacity retention for a CoSn_x NPs lithium-ion full-cell with LiCoO₂ as cathode material at a current of 500 mA_g⁻¹ and (B) galvanic charge/discharge curves for the CoSn_x/LiCoO₂ full cell corresponding to (A) with the average discharge voltage as inset.

Modes for Carrying Out the Invention

According to the process of the invention, first Sn nanoparticles (NPs) and M NPs are synthesized separately by reducing the respective metal chloride with a solution of hydride in an anhydrous polar solvent.

- 5 In a typical synthesis of Sn or M NPs, in particular Co NPs, a suitable amount of a hydride such as NaBH_4 is dissolved in an appropriate amount of anhydrous polar solvent such as 1-methyl-2-pyrrolidone (NMP) and heated while stirred. For the synthesis of Sn NPs, upon reaching the desired temperature, such as 60°C , a solution of a tin salt, such as SnCl_2 , in
10 anhydrous solvent, such as NMP, is injected quickly. For the synthesis of M NPs, upon reaching the desired temperature, such as 150°C for $\text{M}=\text{Co}$ or 120°C for $\text{M}=\text{Mn}$, Fe, Ni, a solution of a metal salt, such as CoCl_2 , MnCl_2 , FeCl_2 , NiCl_2 , in anhydrous solvent, such as NMP, is injected quickly.

- Solid Sn NPs or M NPs are formed immediately. After the injection the
15 respective suspensions are cooled to room temperature, e.g. with a water-ice bath. The respective obtained materials are separated from their solution by centrifugation and washed once with dimethyl sulfoxide (DMSO) and two times with water to remove unreacted NaBH_4 and water-soluble side-products such as NaCl. The respective reaction products can be finally dried in the
20 vacuum oven at room temperature. Typically the reaction yields the desired product in amounts of 67% for Sn NPs, 98% for Co NPs, 36% for Fe NPs, 16% for Mn NPs and 34% for Ni NPs.

- In the above indicated methods the following chemicals in general are suitably applied to obtain Sn NPs or M NPs. However, to account for the
25 different reactivity of MCl_2 and SnCl_2 different reaction temperatures and precursor concentrations are used:

I. As anhydrous solvent other than NMP:

Any amide such as hexamethylphosphoramide, 1,3-dimethyl-2-imidazolidinone or 1,3-dimethyl-3,4,5,6-tetrahydro-2(1H)-pyrimidinone.

II. As substitution for NaBH_4 :

Any alkali or earth alkali hydride such as lithium hydride, sodium hydride, potassium hydride, magnesium hydride, calcium hydride or other
5 metal hydrides such as tributyltinhydride, diisobutyl aluminum hydride, lithium aluminum hydride or lithium triethylborohydride.

III. As substitution for SnCl_2 :

Any tin halide such as tin fluoride, tin bromide, tin iodide; any tin oxide, tin sulfide, sodium stannate trihydrate, or tetrabutyltin.

10 IV. As substitution for MCl_2 :

Any metal halide such as metal fluoride, metal bromide, metal iodide; any metal oxide, metal sulfide or metal sulfate.

The above indicated chemicals may be used alone or in combination with one or more other members of their respective group I to IV.

15 The particles sizes may be influenced by several characteristics such as amount of hydride, reaction temperature and cooling speed.

Depending on the amount of NaBH_4 employed the size of the NPs can be varied, i.e. the higher the amount of NaBH_4 the smaller the particles. In addition, to produce NPs of small sizes with high yield an excess of NaBH_4 is
20 necessary.

Sn NPs or M NPs can also be produced at room temperature, however, the formation of smaller NPs is likely to be favored at elevated temperatures.

Sn NPs with a diameter of approximately 5-10 nm can be obtained by
25 employing about a 96 fold excess of NaBH_4 as reducing agent and fast cooling down directly after the injection of the SnCl_2 .

M NPs with a diameter of approximately 4-10 nm can be obtained by employing about a 4-8 fold excess of NaBH_4 as reducing agent and fast cooling down directly after the injection of the MCl_2 .

5 The fast cooling down can be achieved by any adequate cooling technique known to the person skilled in the art.

In addition, it has been found that such syntheses of Sn or M NPs may be performed in air which significantly reduces the costs (material as well as working hours).

10 Besides of being easy to perform and comparatively cheap the method for preparing the Sn NPs and M NPs used in the present invention has several advantages compared with methods described in literature. The advantages of this synthetic procedure are the following:

I. No surfactant needs to be used.

II. Reaction can also be done in air.

15 III. Inexpensive and safe chemicals: the herein preferably used NaBH_4 is the least expensive metal hydride,

IV. Washing procedure: the obtained Sn or M NPs are simply washed with water in air.

20 V. Depending on the excess of NaBH_4 used and the reaction temperature, the size of the particles can be tuned.

After the synthesis of the Sn NPs and of the M NPs, mixtures of Sn NPs and M NPs are prepared. The molar ratio of M nanoparticles and Sn nanoparticles in these mixtures is comprised between 1:1 and 1:3.

25 The mixtures of Sn NPs and M NPs are ball-milled either in air or under nitrogen with the goal to alloy the materials and obtain MSn_x nanoparticles. Advantageously, the M nanoparticles and Sn nanoparticles are ball-milled for 2 to 4 hours, at a frequency of 1800 to 2400 rpm.

An anode may be prepared by mixing MSn_x NPs, carbon black, CMC and water, preferably by using a ball-mill for e.g. 1 h. The aqueous slurry obtained is then coated on a current collector like a Cu current collector, and subsequently dried, e.g. overnight at 80°C under vacuum prior to battery assembly.

Experimental part

I. Materials used

Chemicals and solvents: Tin chloride SnCl_2 (99.9%, Alfa Aesar), CoCl_2 (98%, Sigma-Aldrich), 1-methyl-2-pyrrolidone (NMP, anhydrous, 99.5%, Fisher BioReagents).

Battery components: Carbon black (CB, Super C65, provided by TIMCAL), carboxymethylcellulose (CMC, Grade: 2200, Daicel Fine Chem Ltd.); fluoroethylene carbonate (FEC, Solvay, battery grade), 1 M solution of LiPF_6 in ethylene carbonate/dimethyl carbonate (EC:DMC : 1:1, Merck, battery grade), glass microfiber separator (GF/D, Whatman, Cu foil ($9\text{ }\mu\text{m}$, MTI Corporation)

II. Methods

20 Synthesis of CoSn_x NPs

Example 1: Synthesis of CoSn_2 Nanocrystals (NCs)

According to the invention, the synthesis of CoSn_2 NCs comprises the synthesis of Sn NCs, the synthesis of Co NPs, and the synthesis of CoSn_2 NCs by ball-milling of the Sn NCs and Co NPs:

25 Synthesis of Sn NCs:

In a typical synthesis of Sn NCs, 96 mmol of NaBH_4 were dissolved in 85 mL anhydrous NMP and heated to 60°C under nitrogen, while stirred mechanically. Upon reaching 60°C a solution of 1 mmol SnCl_2 previously

dissolved in anhydrous NMP was injected quickly and the reaction mixture was immediately cooled to room temperature using a water-ice bath. The reaction product was separated from the solution by centrifugation and washed once with dimethyl sulfoxide and then two times with water. Sn NCs
5 were obtained.

The reaction yield was 80 mg (67%). The XRD pattern of the obtained product showed only peaks corresponding to crystalline β -Sn (Figure 1, indexed to tetragonal Sn, space group *I41/amd* (141), $a = 5.831 \text{ \AA}$, $c = 3.182 \text{ \AA}$, ICDD PDF entry No.: 00-004-0673). Analysis of the reaction product by
10 TEM showed that particles were polydisperse with sizes of 5-10 nm (Figure 3B).

Synthesis of Co NPs:

In a typical synthesis of Co NPs, a similar procedure was used as for
15 Sn NCs with modifications, in particular reaction temperature and precursor concentrations): 32 mmol of NaBH_4 were dissolved in 15 mL anhydrous NMP and heated to 150°C under nitrogen, while stirred mechanically. Upon reaching 150°C a solution of 8 mmol CoCl_2 previously dissolved in anhydrous NMP was injected quickly and the reaction mixture was immediately cooled
20 to room temperature using a water-ice bath. The reaction product was separated from the solution by centrifugation and washed once with dimethyl sulfoxide and then two times with water. Co NPs were obtained.

The reaction yield was 460 mg (98%). The XRD pattern of the obtained product showed that amorphous Co NPs were obtained. Figure 2 shows the
25 EDX-spectrum of amorphous Co NPs. The peak corresponding to S (about 1wt% of the sample) might be attributed to residual DMSO. Analysis of the reaction product by TEM showed that particles were polydisperse with sizes of 4-7 nm range (Figure 3A).

Synthesis of CoSn_2 Nanocrystals (NCs):

For the preparation of Co-Sn based NCs, 1.4 mmol of Sn NCs prepared as above were ball-milled for 4 hours with 0.7 mmol of Co NPs prepared as above, at a frequency of 30 s⁻¹. The beaker for ball-milling was loaded under nitrogen atmosphere and sealed.

- 5 The reaction yield was 200 mg (96%). The XRD pattern of the obtained product showed that ball-milling under inert conditions resulted in the formation of crystalline CoSn₂ nanoalloys (reference patterns: tetragonal SnO₂, space group *P42/mnm* (136), *a* = 4.7391 Å, *c* = 3.1869 Å, ICDD PDF entry 00-077-0448; tetragonal CoSn₂, space group *I4/mcm* (140), *a* = 6.363
10 Å, *c* = 5.456 Å, ICDD PDF entry 00-025-0256). Analysis of the reaction product by TEM showed that particles were polydisperse with sizes of 6-20 nm (Figure 3D).

Example 2: Synthesis of CoSn_x Nanoparticles (NPs)

- 15 For the preparation of Co-Sn based NPs, 1.4 mmol of Sn NCs prepared as above were ball-milled for 4 hours with 0.7 mmol of Co NPs prepared as above, at a frequency of 30 s⁻¹. The beaker for ball-milling was loaded in air.

- 20 The reaction yield was 200 mg (96%). The XRD pattern of the obtained product showed that ball-milling in air resulted in the formation of amorphous CoSn_x NPs. The major fraction of the samples amorphizes, with only small features corresponding to SnO₂ at 34° and CoSn₂ at 35.5°. Analysis of the reaction product by TEM showed that particles were polydisperse with sizes of 6-20 nm (Figure 3C).

25

III. Preparation of Co-Sn-based electrodes, cell assembly and electrochemical measurements

For electrode preparation, aqueous slurries were prepared by mixing the respective NPs (64 wt.%) with CB (21 wt.%), CMC (15 wt.%) and water

as solvent by ball-milling at 500 rpm for 1 hour. The resulting slurries were coated onto copper current collectors, which were dried at 80°C under vacuum for 12 hours prior to battery assembly. Electrochemical measurements were conducted in air tight coin-type cells assembled in an Ar-filled glove box ($O_2 < 0.1$ ppm, $H_2O < 0.1$ ppm) using either elemental lithium for lithium-ion half-cell tests or $LiCoO_2$ on aluminium foil (MTI) for lithium-ion full-cell tests. A piece of glass microfiber was used as separator. As electrolyte 1M $LiPF_6$ in EC:DMC with 3% FEC was used. FEC is added to the electrolyte to improve cycling stability. Galvanostatic cycling tests were carried out at room temperature on MPG2 multi-channel workstation (BioLogic). Capacities were normalized by the mass of Co-Sn nanoparticles for both half and full-cell tests, excluding CB and the binder.

IV. Characterization

Transmission Electron Microscopy (TEM) images were obtained with a Philips CM30 TEM microscope at 300 kV using carbon-coated Cu grids as substrates (Ted-Pella). Energy-dispersive X-ray spectroscopy (EDX) measurements were carried out using a NanoSEM 230. Powder X-ray diffraction (XRD) was measured on a STOE STADI P powder X-ray diffractometer.

V. Electrochemical results

Figure 4 shows the capacity retention of Co-Sn based NPs over 1500 cycles at a high current of 1984 mA g^{-1} in the potential range 0.005–1.0 V. The current of 1984 mA g^{-1} corresponds to a rate of 2C for Sn based on the theoretical capacity of 992 mA h g^{-1} for the formation of $Li_{4.4}Sn$. Assuming that Co does not contribute to the capacity, the theoretical capacity of $CoSn_x$ NPs and $CoSn_2$ NCs is with 795 mA h g^{-1} accordingly lower compared to pure Sn. For galvanostatic cycling tests the upper cut-off potential was limited to 1.0 V

in order to only include processes corresponding to high energy density in full-cells. As can be seen in Figure 4 for galvanostatic cycling at 1984 mA g^{-1} Sn NCs as well as CoSn $_x$ NPs and CoSn $_2$ NCs show capacities of ~ 570 mA $h g^{-1}$, after rapid increase of the capacity during the first 100 cycles. Whereas Sn NCs show significant capacity fading after 400 cycles, Co-Sn based NPs show much better capacity retention. In particular, for CoSn $_2$ NCs after 1500 cycles still 462 mA $h g^{-1}$ are retained. For CoSn $_x$ NPs capacity retention is even better with 525 mA $h g^{-1}$ corresponding to only 8% fading over 1500 cycles at a current of 1984 mA g^{-1} . Therefore the CoSn $_x$ NPs obtained by the method of the invention have an ultrahigh cycling stability. The superior cycling stability of CoSn $_x$ NPs involving Co compared to pure Sn NCs might be attributed to two effects. Due to the fact that Co does not form lithium-alloys it can serve as inactive matrix during cycling and therefore buffer the volume changes caused by the lithiation/delithiation of Sn. Moreover, the presence of Co can prevent Sn NCs from aggregation and therefore further improve cycling stability. The difference between CoSn $_2$ NCs and CoSn $_x$ NPs in terms of cycling stability might be attributed to the fact that CoSn $_x$ NPs are more oxidized due to their preparation by ball-milling in air. The higher content of oxides possibly results in the formation of a more effective Li $_2$ O matrix to buffer volume changes and inhibit sintering of Sn domains during cycling. It should be noted that for all three systems the average coulombic efficiency is 99.6% during cycling, after values of $\sim 30\%$ were obtained for the first discharge cycle due to the solid electrolyte formation. The average delithiation potential for Sn NCs, CoSn $_2$ NCs and CoSn $_x$ NPs are equally low with a stable value of ~ 0.5 V vs. Li $^+$ /Li during cycling (Figures 5A to 5C and Figures 6A to 6C).

To evaluate the rate capability of the Co-Sn based NPs, galvanostatic cycling tests at current rates between 0.2C to 10C were carried out (Figure 7, 1C = 992 mA g^{-1}). Due to the small size of the NPs and therefore enhanced reaction kinetics in all cases similarly good rate capability was observed, though for currents of 0.5C–2C Sn NCs showed by ~ 50 mA $h g^{-1}$ lower

capacities compared to CoSn_2 NCs. For rates as high as 10C all three materials still retain a capacity of $\sim 350 \text{ mAhg}^{-1}$. Interestingly, it can be observed that at such high current capacities increase during cycling, resulting in same or even higher capacities were obtained during stepwise decrease of the rate back to 0.2C. Especially for CoSn_x NPs the slight difference in capacity to CoSn_2 NCs observed initially at the rates of 0.5C–2C diminishes fully during cycling.

In order to test the applicability of Co-Sn based NPs under more practical conditions, anode-limited full-cell tests using LiCoO_2 as cathode were carried out. CoSn_x NPs were chosen as anode material, because of their superior capacity retention compared to Sn and CoSn_2 NCs. Herein, all capacities and currents are related to the mass of CoSn_x NPs. Full-cells of CoSn_x NPs/ LiCoO_2 were initially charged to 2000 mAhg^{-1} to account for the irreversible charge loss in the first cycle. For subsequent cycling charge and discharge were limited to 500 mAhg^{-1} . Cycled under these conditions at a current of 500 mA g^{-1} CoSn_x NPs show stable capacities with an average discharge voltage of 3.2 V for 50 cycles. Based on the anode capacity and discharge voltage one roughly estimates the specific energy density of CoSn_x NPs to be comparable to graphite (372 mAhg^{-1} , 3.6 V vs. LiCoO_2). However, given the much higher density of bulk β -Sn ($\sim 7.3 \text{ gcm}^{-3}$) and Co ($\sim 8.9 \text{ gcm}^{-3}$) compared to graphite ($\sim 2.2 \text{ gcm}^{-3}$) using CoSn_x NPs can potentially improve the volumetric energy density by up to factor 4.

Figure 8 shows the electrochemical performance of a CoSn_x NPs lithium-ion full-cell with LiCoO_2 as cathode material: Figure 8A: Capacity retention at a current of 500 mA g^{-1} . Figure 8B: Galvanostatic charge/discharge curves for the $\text{SnSb}/\text{LiCoO}_2$ full cell corresponding to (A) with the average discharge voltage as inset. Cells were cycled with limitation of charge and discharge capacity to 500 mAhg^{-1} . Displayed capacities and currents are related to the mass of CoSn_x NPs.

In conclusion, the method of the invention allows to synthesize Co NPs and Sn NCs with diameters ≤ 10 nm *via* simple reduction of the respective metal chlorides with NaBH_4 in NMP and subsequently converted them into intermetallic crystalline and amorphous Co-Sn nanoalloys by ball-milling.

5 Though CoSn_2 NCs show good cycling stability for several hundred cycles, amorphous CoSn_x NPs show outstanding capacity retention with only 8% fading over 1500 cycles at 1984 mAhg^{-1} . In addition, tested in lithium-ion full-cells with LiCoO_2 as cathode material CoSn_x NPs provide stable capacities of 500 mAhg^{-1} with an average discharge voltage of 3.2 V. Given the
10 inexpensive and easily upscalable preparation method and their excellent electrochemical properties characterized by high cyclability as well as high volumetric and specific energy densities, the herein presented CoSn_x NPs have a great potential as high-performance anode materials for Li-ion and Na-ion batteries

15 While there are shown and described presently preferred embodiments of the invention, it is to be distinctly understood that the invention is not limited thereto but may be otherwise variously embodied and practiced within the scope of the following claims.

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CLAIMS

1. A method for the production of MSn_x nanoparticles, wherein

M is Co, Mn, Fe, Ni, Cu, In, Al, Ge, Pb, Bi, or Ga; and

$0 < x \leq 10$;

the method comprising separately synthesizing Sn and M nanoparticles by, in either order:

- synthesizing the Sn nanoparticles by reducing a tin salt with a solution of a hydride in an anhydrous polar solvent, separating the solid Sn nanoparticles formed from the solution, and washing the Sn nanoparticles, and

- synthesizing the M nanoparticles by reducing a metal salt with a solution of a hydride in an anhydrous polar solvent, separating the solid M nanoparticles formed from the solution, and washing the M nanoparticles, and then

- mechanically mixing said Sn nanoparticles and said M nanoparticles to obtain the MSn_x nanoparticles, wherein the mechanical mixing is obtained by ball-milling in air.

2. The method according to claim 1, wherein the molar ratio of M nanoparticles and Sn nanoparticles for the mechanical mixing step is comprised between 1:1 and 1:3.

3. The method according to claim 1, wherein M is Co.

4. The method according to claim 1, wherein the reduction reaction of the tin salt is performed at a temperature comprised between 50°C and 70°C.

5. The method according to claim 1, wherein the reduction reaction of the metal salt is performed at a temperature comprised between 60°C and 180°C.

6. The method according to claim 1, wherein the hydride is NaBH_4 , lithium hydride, sodium hydride, potassium hydride, magnesium hydride, calcium hydride, tributyltinhydride, diisobutyl aluminum hydride, lithium aluminum hydride, lithium triethylborohydride or mixtures thereof.
7. The method according to claim 6, wherein the hydride is NaBH_4 .
8. The method according to claim 1, wherein the anhydrous polar solvent is 1-methyl-2-pyrrolidone (NMP), hexamethylphosphoramide, 1,3-dimethyl-2-imidazolidinone, 1,3-dimethyl-3,4,5,6-tetrahydro-2(1H)-pyrimidinone, dimethylsulfoxide, sulfolane, glyme, diglyme, triethylene glycol dimethylether, or mixtures thereof.
9. The method according to claim 8, wherein the anhydrous polar solvent is 1-methyl-2-pyrrolidone (NMP).
10. The method according to claim 1, wherein the tin salt is tin chloride, tin fluoride, tin bromide, tin iodide, tin oxide, tin sulfide, sodium stannate trihydrate, tetrabutyltin, or mixtures thereof.
11. The method according to claim 10, wherein the tin salt is tin chloride.
12. The method according to claim 1, wherein the metal salt is M chloride or mixtures thereof.
13. The method according to claim 12, wherein the metal salt is Co chloride.
14. The method according to claim 1, wherein the reduction reaction is performed in inert gas.
15. The method according to claim 14, wherein the reduction reaction is performed under nitrogen.

16. The method according to claim 1, wherein the reduction reaction is performed in air.

17. The method according to claim 1, wherein the step of synthesizing the Sn nanoparticles comprises the steps of:

- preparing a solution of hydride in anhydrous solvent and at least one solution of tin salt in anhydrous solvent,

- heating the solution of hydride to the reaction temperature of the reduction reaction of the tin salt, and

- starting the reduction reaction when the reaction temperature of the reduction reaction of the tin salt is reached by injection of the one or more tin salt solutions into the solution of hydride to generate a reaction mixture.

18. The method according to claim 1, wherein the step of synthesizing the Sn nanoparticles comprises the steps of:

- preparing a solution of one or more tin salts in anhydrous solvent and at least one solution of hydride in anhydrous solvent,

- heating the solution of tin salts to the reaction temperature of the reduction reaction of the tin salt, and

- starting the reduction reaction when the reaction temperature of the reduction reaction of the tin salt is reached by injection of the hydride solution into the solution of one or more tin salts to generate a reaction mixture.

19. The method according to claim 1, wherein the step of synthesizing the M nanoparticles comprises the steps of:

- preparing a solution of hydride in anhydrous solvent and at least one solution of metal salt in anhydrous solvent,

- heating the solution of hydride to the reaction temperature of the reduction reaction of the metal salt, and

- starting the reduction reaction when the reaction temperature of the reduction reaction of the metal salt is reached by injection of the one or more metal salt solutions into the solution of hydride to generate a reaction mixture.

20. The method according to claim 1, wherein the step of synthesizing the M nanoparticles comprises the steps of:

- preparing a solution of one or more metal salts in anhydrous solvent and at least one solution of hydride in anhydrous solvent,

- heating the solution of metal salts to the reaction temperature of the reduction reaction of the metal salt, and

- starting the reduction reaction when the reaction temperature of the reduction reaction of the metal salt is reached by injection of the hydride solution into the solution of one or more metal salts to generate a reaction mixture.

21. The method according to claim 17, wherein the reaction mixture is cooled to room temperature after injection.

22. A method for producing an anode comprising performing the method of any one of claims 1 to 21 for producing MSn_x nanoparticles, mixing such obtained MSn_x nanoparticles, carbon black, carboxy methyl cellulose (CMC) and water to obtain an aqueous slurry, coating said aqueous slurry obtained on a current collector and drying.

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Fig. 1

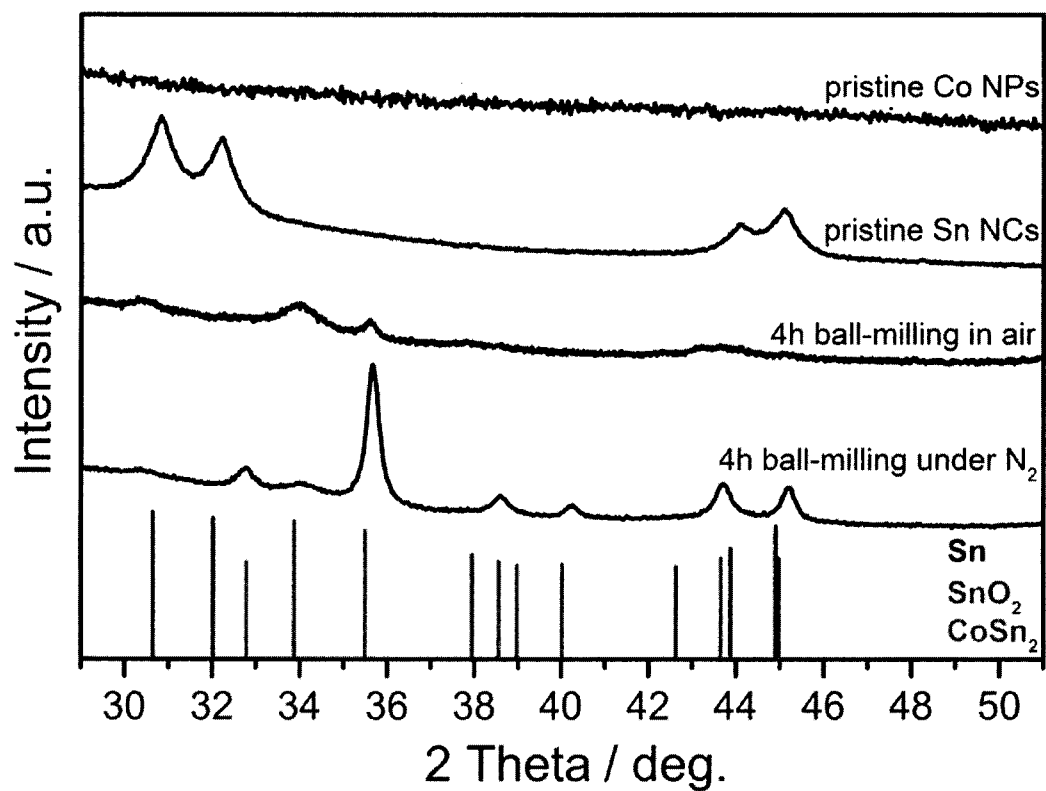
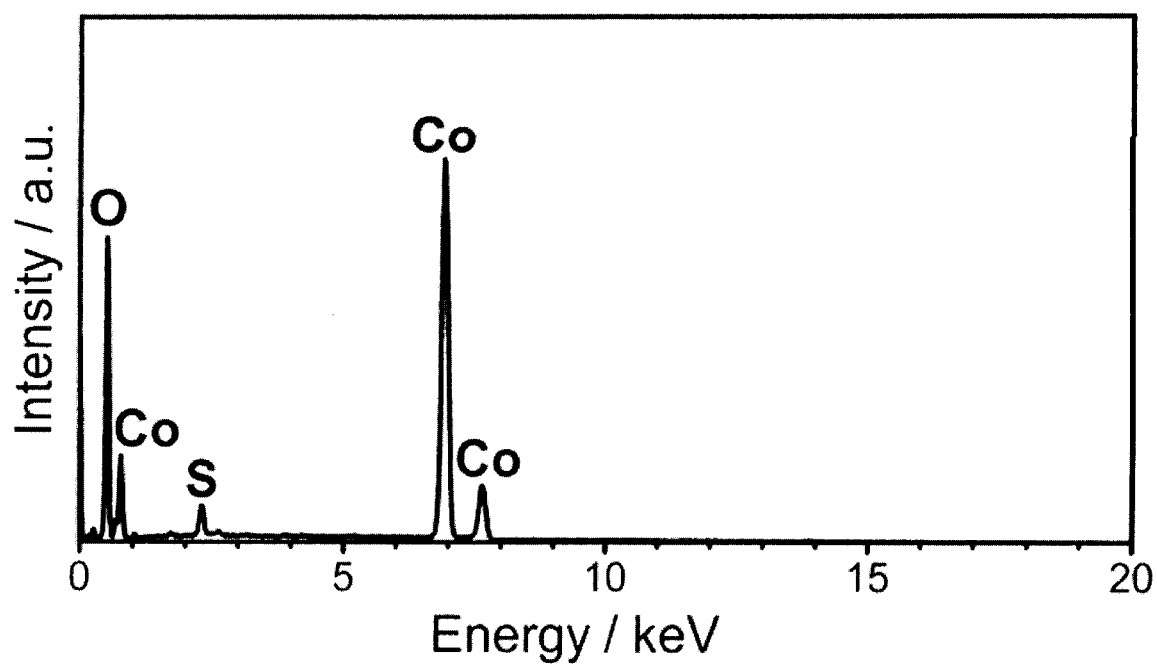


Fig. 2



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Fig. 3

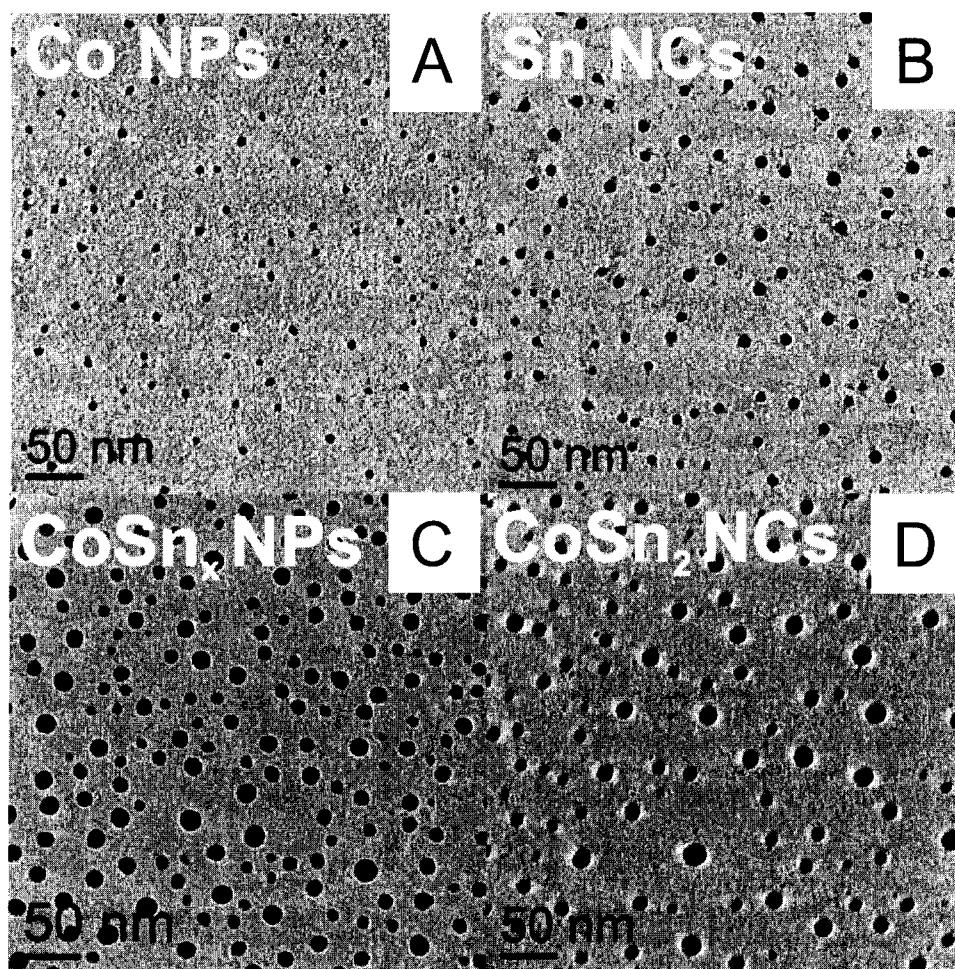


Fig. 4

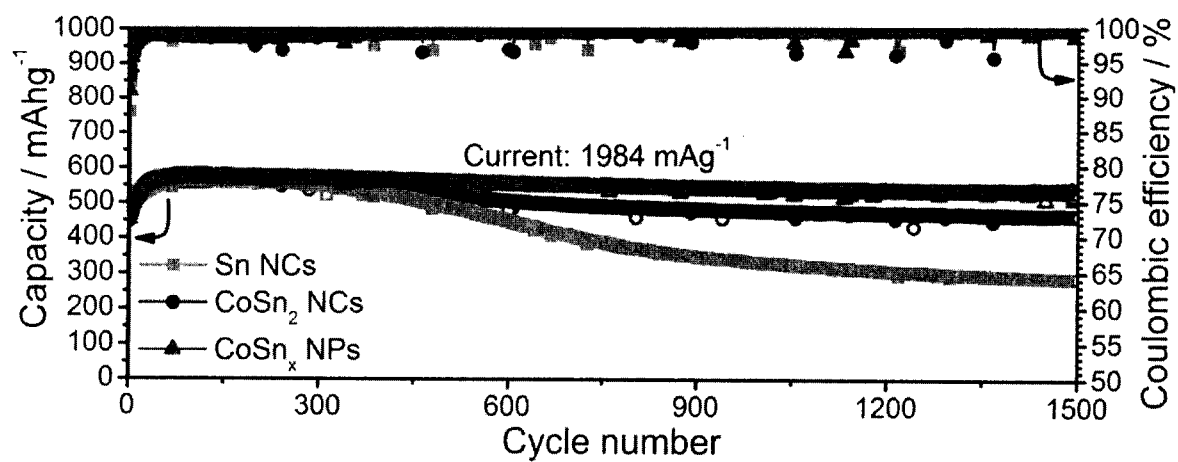


Fig. 5A

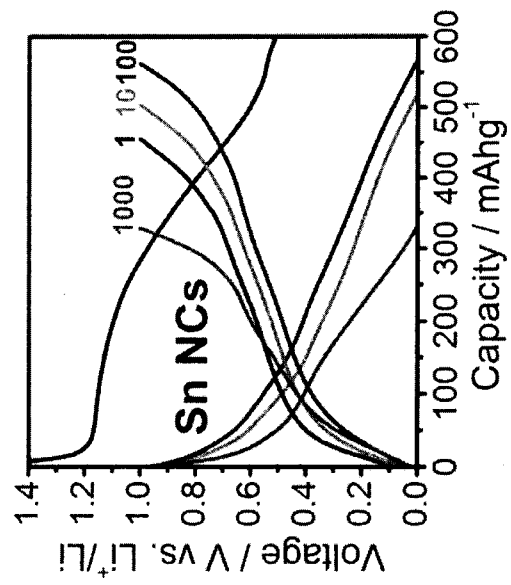


Fig. 5B

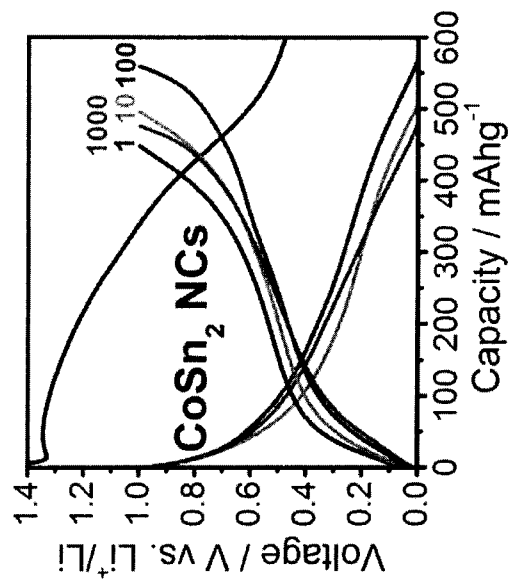
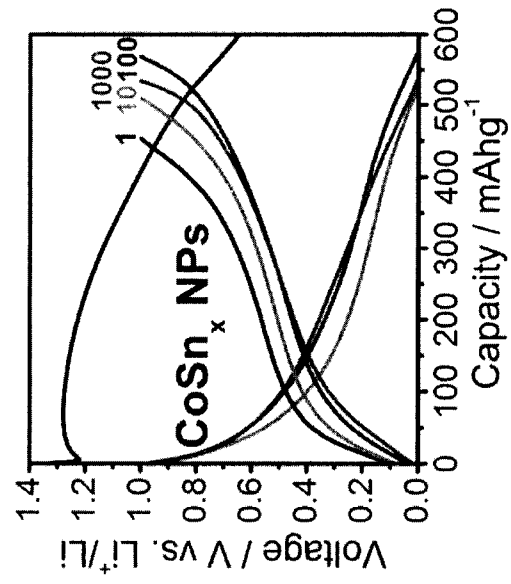


Fig. 5C



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Fig. 6A

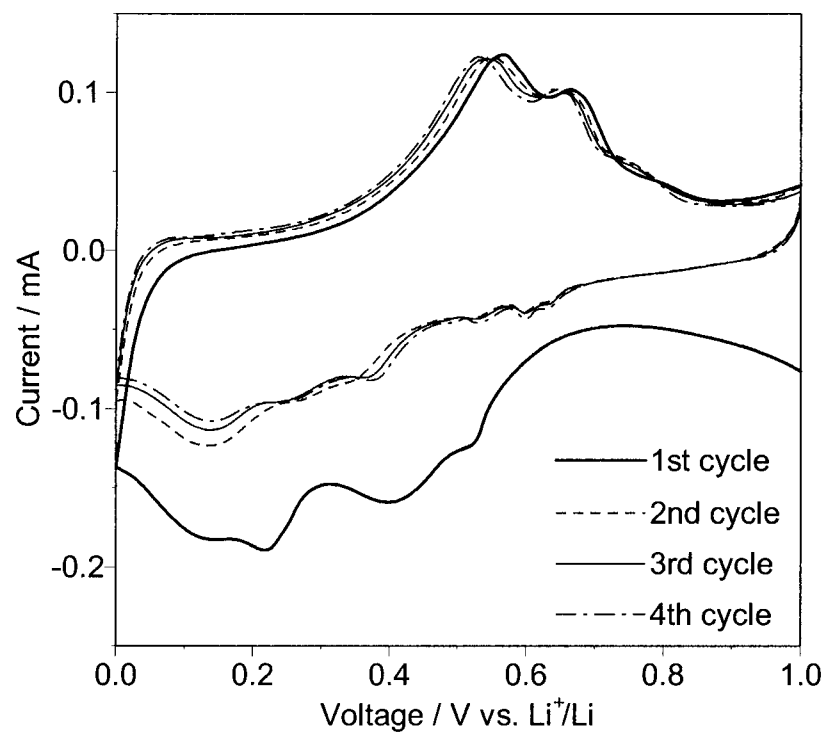
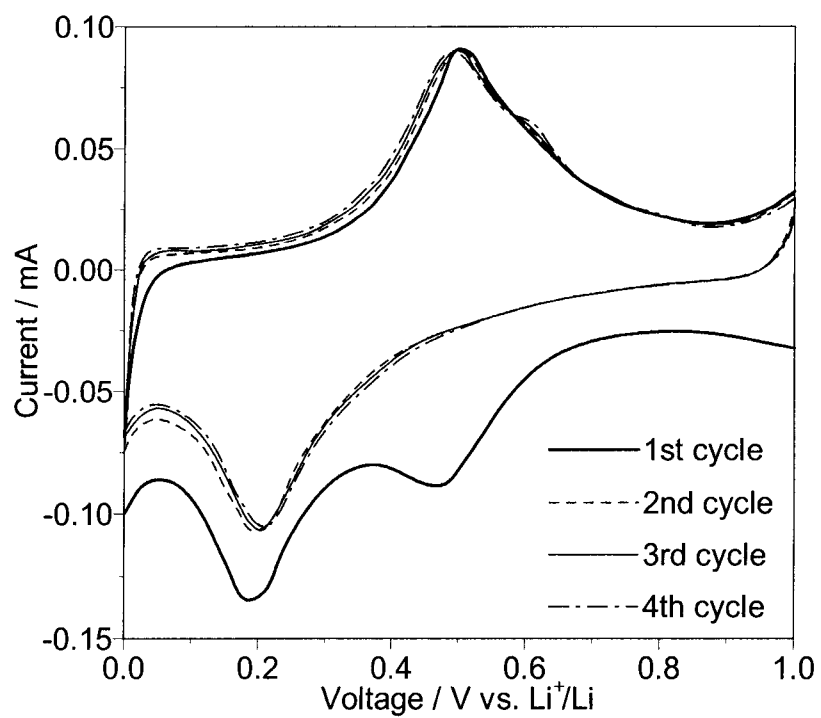


Fig. 6B



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Fig. 6C

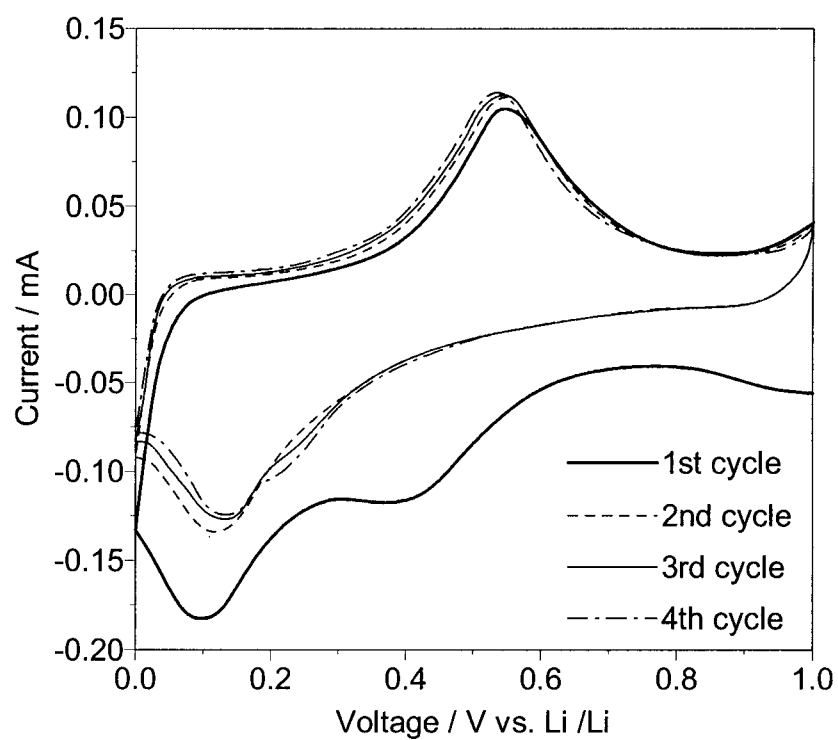
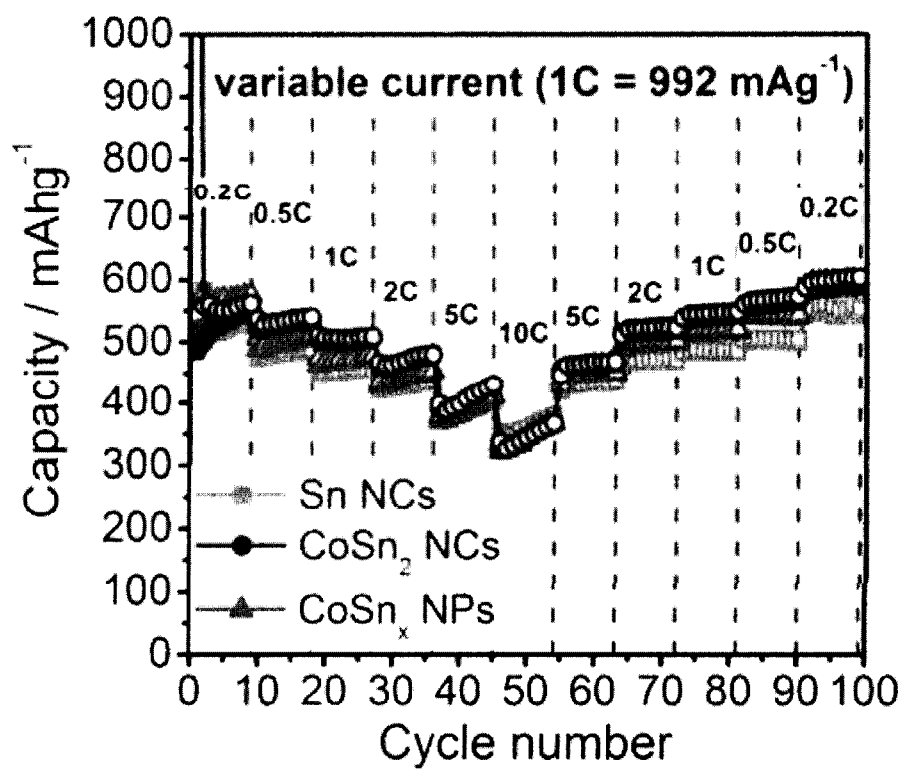


Fig. 7



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Fig. 8A

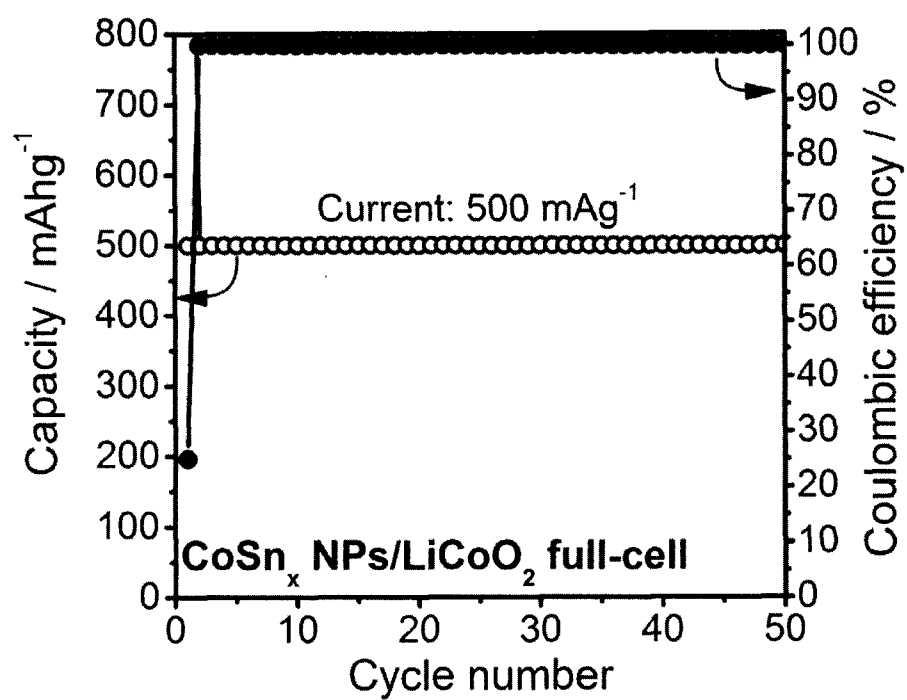


Fig. 8B

