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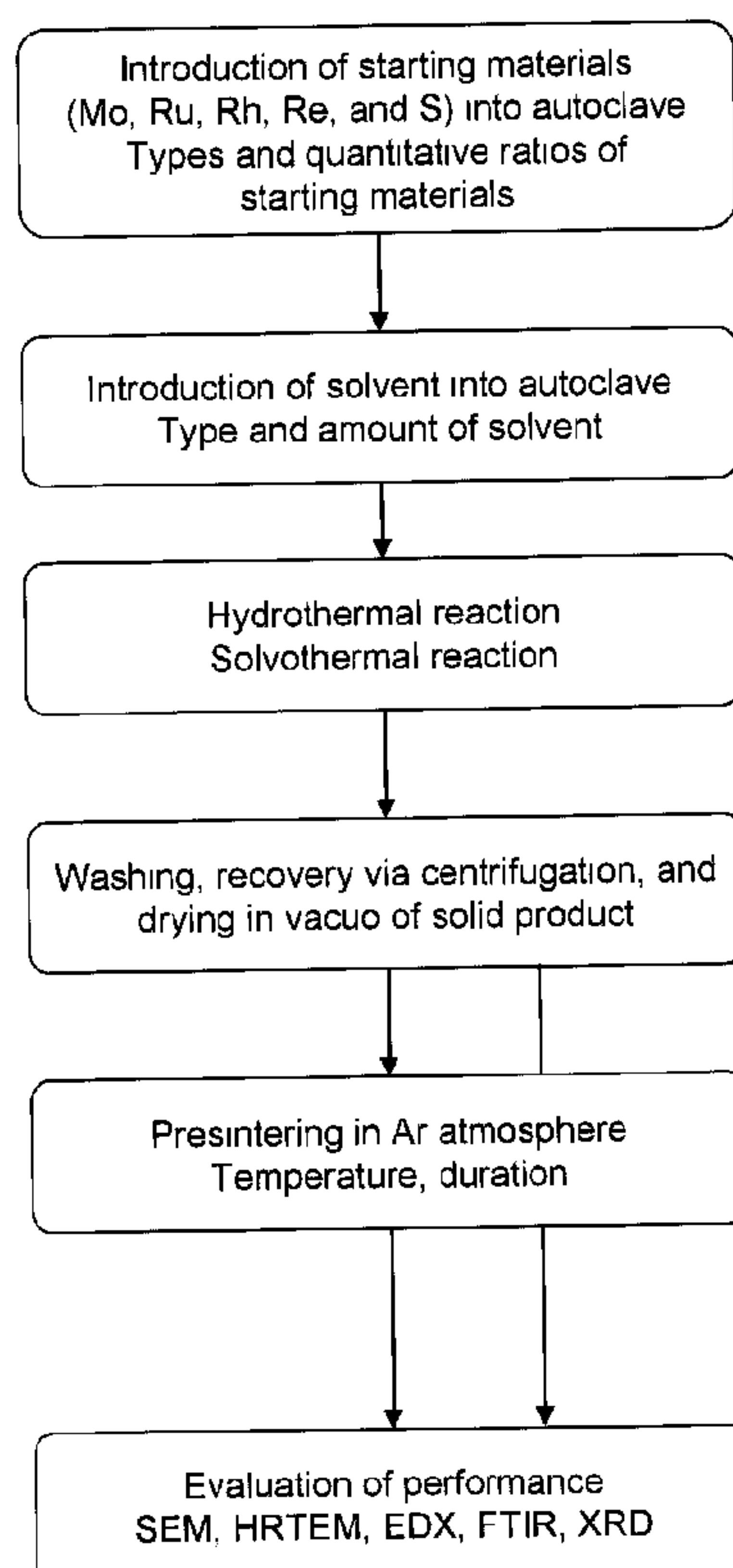
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(54) Titre : COMPOSITE DE FINES PARTICULES, PROCEDE SERVANT A PRODUIRE LE COMPOSITE DE FINES PARTICULES, CATALYSEUR POUR PILE A COMBUSTIBLE A ELECTROLYTE POLYMERIQUE SOLIDE ET PILE A COMBUSTIBLE A ELECTROLYTE POLYMERIQUE SOLIDE

(54) Title: FINE PARTICLE COMPOSITE, METHOD FOR PRODUCING THE SAME, CATALYST USED FOR SOLID POLYMER FUEL CELL, AND SOLID POLYMER FUEL CELL



(57) Abrégé/Abstract:

This invention provides a process for producing a fine-particle composite comprising a fine particle of a sulfide or a composite sulfide of one or more elements selected from molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) and



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electroconductive fine particles. The production process comprises the step of preparing a solvent mixed liquid from an electroconductive carbon powder, one or more compounds containing an element selected from molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re), and a compound containing sulfur (S), and the step of subjecting the solvent mixed liquid to a hydrothermal reaction or a solvothermal reaction at a pressure and a temperature that bring water or the solvent to a supercritical state or a subcritical state.

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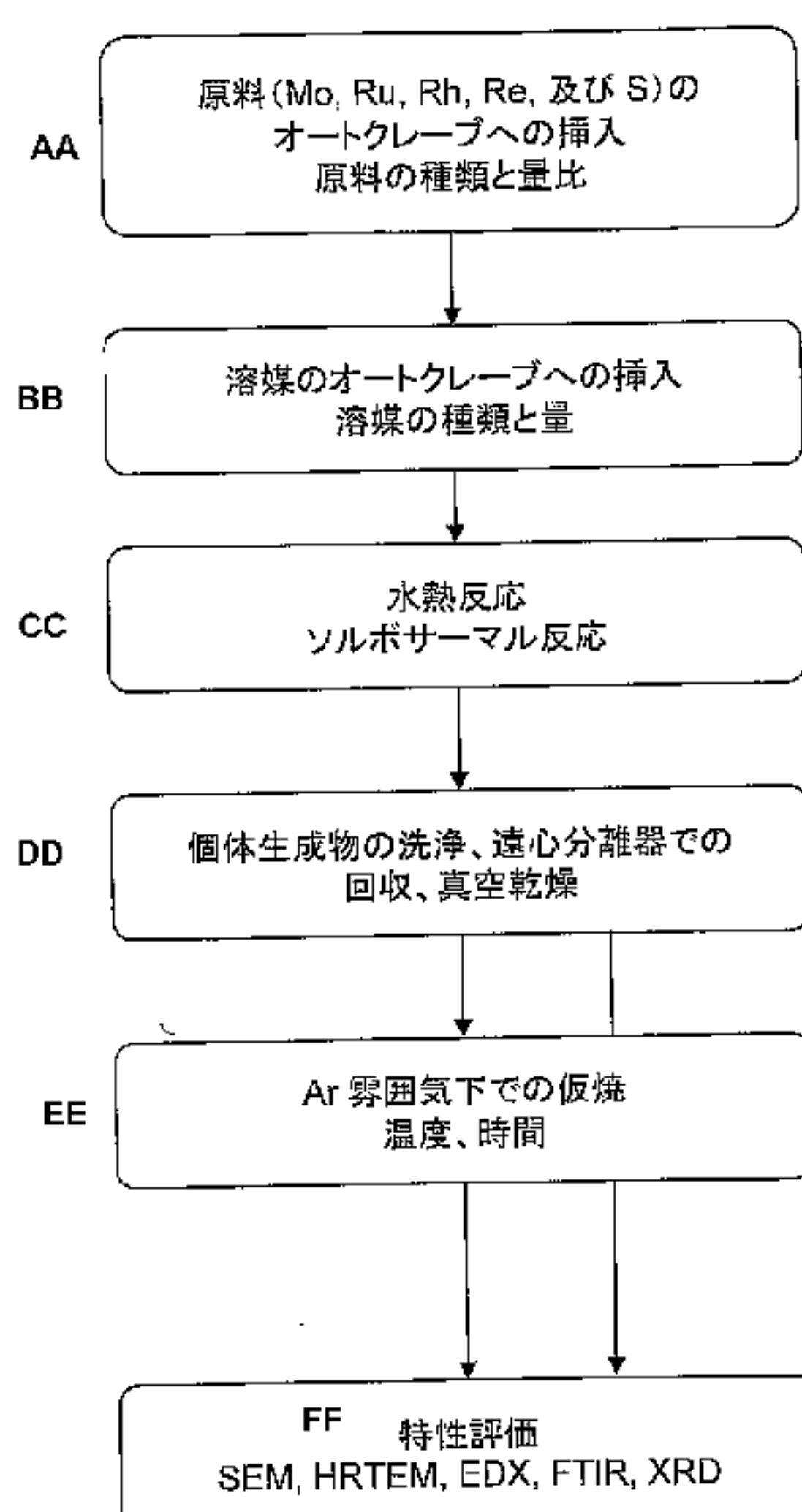
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(54) Title: FINE-PARTICLE COMPOSITE, PROCESS FOR PRODUCING THE FINE-PARTICLE COMPOSITE, CATALYST FOR SOLID POLYMER ELECTROLYTE FUEL CELL, AND SOLID POLYMER ELECTROLYTE FUEL CELL

(54) 発明の名称: 微粒子コンポジット、その製造方法、固体高分子型燃料電池用触媒、及び固体高分子型燃料電池

図 1



AA INTRODUCTION OF RAW MATERIALS (Mo, Ru, Rh, Re, and S) INTO AUTOCLAVE
TYPE AND AMOUNT RATIO OF RAW MATERIALS
BB INTRODUCTION OF SOLVENT INTO AUTOCLAVE
TYPE AND AMOUNT OF SOLVENT
CC HYDROTHERMAL REACTION
SOLVOTHERMAL REACTION
DD WASHING OF SOLID PRODUCT, RECOVERY IN CENTRIFUGE, AND VACUUM DRYING
EE CALCINATION UNDER Ar ATMOSPHERE
TEMP., TIME
FF EVALUATION OF CHARACTERISTICS

(57) Abstract: This invention provides a process for producing a fine-particle composite comprising a fine particle of a sulfide or a composite sulfide of one or more elements selected from molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) and electroconductive fine particles. The production process comprises the step of preparing a solvent mixed liquid from an electroconductive carbon powder, one or more compounds containing an element selected from molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re), and a compound containing sulfur (S), and the step of subjecting the solvent mixed liquid to a hydrothermal reaction or a solvothermal reaction at a pressure and a temperature that bring water or the solvent to a supercritical state or a subcritical state.

(57) 要約: 導電性炭素粉末と、モリブデン (Mo)、ロジウム (Rh)、ルテニウム (Ru)、レニウム (Re) から選択される元素を含む化合物の 1 種以上と、硫黄 (S) を含む化合物とから、溶媒混合液を作製する工程と、該溶媒混合液を水又は溶媒の超臨界状態または亜臨界状態とする圧力および温度で水熱反応又はソルボサーマル反応させる工程とを含むことにより、モリブデン (Mo)、ロジウム (Rh)、ルテニウム (Ru)、レニウム (Re) から選択される 1 種以上の元素の硫化物又は複合硫化物の微粒子と、導電性微粒子とを含む微粒子コンポジットを得ることができる。

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DESCRIPTION

FINE PARTICLE COMPOSITE, METHOD FOR PRODUCING THE SAME,
CATALYST USED FOR SOLID POLYMER FUEL CELL, AND
SOLID POLYMER FUEL CELL

Technical Field

The present invention relates to a fine particle composite comprising fine particles of a sulfide or sulfide complex comprising at least one element selected from the group consisting of molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re), and a method for producing the same. Also, the present invention relates to a catalyst used for a solid polymer fuel cell and a solid polymer fuel cell comprising the fine particle composite.

Background Art

Hydrothermal and solvothermal reactions have drawn attention as means for synthesizing compounds. For example, JP Patent Publication (kokai) No. H11-288732 A (1999) discloses a method for preparing zinc sulfide particles having multiply twinned structures and an average particle diameter of 5 nm to 20 μm via a hydrothermal reaction of a sulfur ion and a zinc ion using water as a reaction solvent at 150°C to 370°C during the process of particle growth.

Various chalcogenide compounds have drawn attention as alternatives to existing expensive platinum catalysts. Catalysts used for polymer electrolyte fuel cells are mainly platinum and platinum-alloy-based catalysts. Specifically, catalysts in which a platinum-containing noble metal is supported by carbon black have been used. In terms of practical applications of polymer electrolyte fuel cells, one problem relates to the cost of materials. A means to solve such problem involves the reduction of platinum content.

Recently, low-cost fuel cell catalysts have been developed via a reaction that

produces water as a result of four-electron reduction of oxygen, which results in elimination of the need for expensive platinum catalysts. *Electrochimica Acta*, vol. 39, No. 11/12, pp. 1647-1653, 1994 discloses that a catalyst comprising a chalcogen element is excellent in terms of four-electron reduction performance and suggests that such catalyst be applied to fuel cells. Specifically, *Electrochimica Acta*, vol. 39, No. 11/12, pp. 1647-1653, 1994 discloses a Mo-Ru-Se ternary electrode catalyst and a method for synthesizing the same.

Also, JP Patent Publication (kohyo) No. 2001-502467 A discloses, as a platinum (Pt) catalyst substitute, an electrode catalyst comprising at least one transition metal and a chalcogen. An example of a transition metal is Ru and an example of a chalcogen is S or Se. It is also disclosed that, in such case, the Ru:Se molar ratio is from 0.5:1 to 2:1 and the stoichiometric number "n" of $(\text{Ru})_n\text{Se}$ is 1.5 to 2.

Further, JP Patent Publication (kohyo) No. 2004-532734 A discloses, as a Pt catalyst substitute, a fuel cell catalyst material comprising a transition metal that is either Fe or Ru, an organic transition metal complex containing nitrogen, and a chalcogen component such as S.

Further, *J. Chem. Soc., Faraday Trans.*, 1996, 92 (21), 4311-4319 discloses Ru-S, Mo-S, and Mo-Ru-S binary and ternary electrode catalysts and methods for synthesizing the same.

Further, *Electrochimica Acta*, vol. 45, pp. 4237-4250, 2000 discloses Ru-Mo-S and Ru-Mo-Se ternary chalcogenide electrode catalysts.

Disclosure of the Invention

The present invention is intended to provide a fine particle composite comprising fine particles of a sulfide or sulfide complex comprising a given element and a method for producing the same. The present invention is also intended to apply such fine particle composite to a catalyst used for a fuel cell, and the present invention thus relates to a catalyst used for a solid polymer fuel cell and a solid polymer fuel cell comprising such fine particle composite.

The present inventors discovered that the above object could be attained via a hydrothermal or solvothermal reaction and arrived at the present invention.

Specifically, the first aspect of the present invention concerns a fine particle composite comprising fine particles of a sulfide or sulfide complex comprising at least one element selected from the group consisting of molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) and conductive fine particles. The fine particle composite of the present invention at least comprises the above components. Fine particles of a sulfide or sulfide complex comprising at least one element selected from the group consisting of molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) have catalyst functions in oxygen reduction reactions and conductive fine particles function as catalyst carriers. Accordingly, the fine particle composite of the present invention have carriers and, thus, such fine particle composite are not in particular need of other carriers.

Regarding the fine particle composite of the present invention, the average particle diameter is preferably 1 nm to 1 μ m.

In the fine particle composite of the present invention, a sulfide or sulfide complex comprising at least one element selected from the group consisting of molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) can be configured in various ways. Specifically, such sulfide or sulfide complex can be in the form of single-crystal fine powder.

The single-crystal fine powder of the present invention can be configured in various ways. For example, that of an approximately spherical configuration can be obtained.

Preferable examples of the aforementioned sulfide as a component of the fine particle composite of the present invention include binary compounds selected from among molybdenum sulfide (Mo_2S_2 , MoS_2 , Mo_2S_3 , MoS_3 , or MoS_4), rhodium sulfide ($\text{Rh}_{17}\text{S}_{15}$, Rh_9S_8 , Rh_3S_4 , Rh_2S_3 , or Rh_2S_5), ruthenium sulfide (RuS_2), and rhenium sulfide (ReS_2 or Re_2S_7).

An example of a preferable sulfide complex is a ternary compound represented

by Rh-X-S or Ru-X-S, wherein X is preferably at least one element selected from among molybdenum (Mo), palladium (Pd), selenium (Se), silicon (Si), tantalum (Ta), tellurium (Te), thorium (Th), vanadium (V), zinc (Zn), rhodium (Rh), ruthenium (Ru), antimony (Sb), and tungsten (W). Rh or Ru functions as a catalyst and X functions as a promoter. Among them, particularly preferable examples include Rh-Mo-S and Ru-Mo-S.

Preferable examples of the aforementioned fine particle as a component of the fine particle composite of the present invention include carbon black and/or carbon nanotube.

The second aspect of the present invention concerns a method for producing a fine particle composite comprising fine particles of a sulfide or sulfide complex comprising at least one element selected from the group consisting of molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) and conductive fine particles. The method comprises steps of: preparing a solvent mixture from at least one compound comprising conductive carbon powder, an element selected from among molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re), and a sulfur (S)-containing compound; and performing a hydrothermal or solvothermal reaction at a pressure and temperature that converts the solvent mixture into a supercritical or subcritical water or solvent.

Solvents used for a solvothermal reaction are not limited, and examples of such a solvent include xylene, acetone, and chloroform.

In the present invention, the hydrothermal or solvothermal reaction is preferably carried out at 200°C to 600°C.

Also, thermal treatment in an inert gas atmosphere at 300°C to 800°C following the step of a hydrothermal or solvothermal reaction can improve crystallinity, thereby dispersing residues of starting compounds, such as carbonyl groups.

In the present invention, preferable examples of the conductive carbon powder include carbon black and/or carbon nanotube.

The fine particle composite of the present invention can be produced by carrying out the reaction *in situ*. Compared with conventional methods for producing catalysts

used for fuel cells involving combinations of several reactions, the fact that the fine particle composite can be produced by performing all reactions *in situ* is a remarkable advantage of the present invention.

The third aspect of the present invention concerns a catalyst used for a solid polymer fuel cell comprising the fine particle composite. The catalyst of the present invention can serve as a substitute for an expensive platinum catalyst.

The fourth aspect of the present invention concerns a solid polymer fuel cell comprising the above fine particle composite as a catalyst.

Use of the fine particle composite of the present invention comprising fine particles of a sulfide or sulfide complex comprising at least one element selected from the group consisting of molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) and conductive fine particles can be realized in the form of various types of reaction catalysts by utilizing catalytic performance such that it does not require the use of a carrier. For example, such fine particle composite can be utilized for a catalyst for a fuel cell while serving as a cost-effective alternative to an existing platinum catalyst. Further, adequate selection of a dopant element with which the fine particle composite is to be doped leads to improvement in catalytic properties.

By performing all the reaction processes for producing the fine particle composite *in situ*, a catalyst used for a fuel cell, which had heretofore been produced in complicated steps, can be easily manufactured.

Brief Description of the Drawings

Fig. 1 is a flow chart detailing the method of synthesis via a hydrothermal or solvothermal reaction of the present invention.

Fig. 2 shows an XRD pattern of MoS₂ synthesized via a solvothermal reaction.

Fig. 3 shows an SEM photograph of MoS₂ powder synthesized from MoCl₅ precalcined at 400°C for 5 hours.

Fig. 4 shows an XRD pattern of MoS₂ synthesized via a solvothermal reaction.

Fig. 5 shows an SEM photograph of MoS₂ powder synthesized from thiourea

precalcined at 400°C for 5 hours.

Fig. 6 shows XRD patterns of MoS₂ synthesized via a solvothermal reaction (a) and the resultant of precalcination thereof (b, c).

Fig. 7 shows XRD patterns of MoS₂ products synthesized from Mo(CO)₆ and S while varying S:Mo ratios via a solvothermal reaction at 220°C for 10 hours.

Fig. 8 shows XRD patterns of the resultant of precalcination of MoS₂ at 400°C for 5 hours. Such resultants were synthesized from Mo(CO)₆ and S via a solvothermal reaction at 220°C for 10 hours while varying S:Mo ratios.

Fig. 9A shows a scanning electron micrograph of MoS₂ resulting from a solvothermal reaction, and Fig. 9B shows that of a resultant of precalcination thereof at 400°C for 5 hours.

Fig. 10 shows a transmission electron micrograph of a resultant of precalcination, at 400°C for 5 hours, of MoS₂ resulting from a solvothermal reaction.

Fig. 11 shows an XRD pattern of MoS₂ resulting from a solvothermal reaction.

Figs. 12A and 12B each show an electron micrograph of MoS₂ resulting from a solvothermal reaction.

Fig. 13 shows an XRD pattern of MoS₂ hydrothermally synthesized at 220°C for 10 hours with the addition of ammonia.

Fig. 14 shows an XRD pattern of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of MoS₂ hydrothermally synthesized with the addition of ammonia.

Figs. 15A and 15B each show a scanning electron micrograph of MoS₂ (an S:Mo ratio of 2.2:1) hydrothermally synthesized at 220°C for 10 hours with the addition of ammonia.

Fig. 16 shows an XRD pattern of MoS₂ hydrothermally synthesized at 220°C for 10 hours with the addition of sodium hydroxide at an S:Mo ratio of 2.2:1 and that of MoS₂ precalcined at 400°C for 5 hours in an argon stream.

Fig. 17 shows a scanning electron micrograph of MoS₂ hydrothermally synthesized at 220°C for 10 hours in an aqueous solution of 0.6M NaOH (an S:Mo ratio

of 2.2:1).

Fig. 18 shows an XRD pattern of a resultant of a hydrothermal reaction of $(\text{NH}_4)_3[\text{PO}_4\text{Mo}_{12}\text{O}]\cdot 3\text{H}_2\text{O}$ and thiourea and that of a resultant of precalcination thereof.

Figs. 19A and 19B each show a scanning electron micrograph of a resultant of a hydrothermal reaction of $(\text{NH}_4)_3[\text{PO}_4\text{Mo}_{12}\text{O}]\cdot 3\text{H}_2\text{O}$ and thiourea and that of a resultant of precalcination thereof.

Fig. 20 shows the FTIR spectra of a resultant of a hydrothermal reaction of $(\text{NH}_4)_3[\text{PO}_4\text{Mo}_{12}\text{O}]\cdot 3\text{H}_2\text{O}$ and thiourea and that of a resultant of precalcination thereof.

Fig. 21 shows an XRD pattern of a resultant of a hydrothermal reaction of $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot 4\text{H}_2\text{O}$ and thiourea and that of a resultant of precalcination thereof.

Figs. 22A and 22B each show a scanning electron micrograph of a resultant of a hydrothermal reaction of $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot 4\text{H}_2\text{O}$ and thiourea and that of a resultant of precalcination thereof.

Fig. 23 shows the FTIR spectra of a resultant of a hydrothermal reaction of $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot 4\text{H}_2\text{O}$ and thiourea and that of a resultant of precalcination thereof.

Fig. 24 shows an XRD pattern of RuS_2 synthesized via a solvothermal reaction at 220°C for 10 hours while varying S:Ru ratios.

Fig. 25 shows an XRD pattern of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of RuS_2 synthesized via a solvothermal reaction at 220°C for 10 hours.

Figs. 26A, 26B, and 26C each show a scanning electron micrograph of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of RuS_2 synthesized via a solvothermal reaction at 220°C for 10 hours.

Figs. 27A, 27B, 27C, and 27D each show a transmission electron micrograph of a resultant of precalcination of RuS_2 .

Fig. 28 shows the FTIR spectra of RuS_2 synthesized via a solvothermal reaction (an S:Ru ratio of 4:1) and that of a resultant of precalcination thereof at 400°C .

Fig. 29 shows an XRD pattern of RuS_2 resulting from a hydrothermal reaction at 220°C for 10 hours.

Fig. 30 shows an XRD pattern of a resultant of precalcination, at 400°C for 5 hours, of RuS₂ resulting from a hydrothermal reaction at 220°C for 10 hours.

Figs. 31A and 31B each show a scanning electron micrograph of RuS₂ and that of a resultant of precalcination thereof.

Fig. 32 shows an XRD pattern of Rh₂S₃ synthesized via a solvothermal reaction at 220°C for 10 hours.

Fig. 33 shows an XRD pattern of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of Rh₂S₃ synthesized via a solvothermal reaction at 220°C for 10 hours.

Fig. 34 shows an XRD pattern of Rh₂S₃ synthesized via a solvothermal reaction at 220°C for 10 hours at an S:Rh ratio of 5.0:1 and that of a resultant of precalcination thereof in an argon stream at 400°C for 5 hours and at 750°C for 5 hours.

Figs. 35A, 35B, 35C, and 35D each show a scanning electron micrograph of Rh₂S₃ resulting from a solvothermal reaction and a resultant of precalcination thereof.

Fig. 36 shows an XRD pattern of Rh₂S₃ resulting from a hydrothermal reaction and that of a resultant of precalcination thereof.

Figs. 37A and 37B each show an electron micrograph of Rh₂S₃ resulting from a hydrothermal reaction and that of a resultant of precalcination thereof.

Figs. 38A and 38B each show an electron micrograph and an electron diffraction diagram of Rh₂S₃ resulting from a hydrothermal reaction (an S:Rh ratio of 3.0:1).

Figs. 39A and 39B each show an electron micrograph and an electron diffraction diagram of a resultant of calcination of Rh₂S₃ resulting from a hydrothermal reaction at 400°C (an S:Rh ratio of 3.0:1).

Fig. 40 shows the FTIR spectra of hydrothermally synthesized Rh₂S₃ (an S:Rh ratio of 3:1) and a resultant of precalcination thereof at 400°C.

Fig. 41 shows an XRD pattern of ReS₂ synthesized via a solvothermal reaction at 220°C for 10 hours.

Fig. 42 shows an XRD pattern of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of ReS₂ synthesized via a solvothermal reaction at 220°C

for 10 hours.

Fig. 43 shows an XRD pattern of ReS_2 obtained at an S:Re ratio of 4:1 and that of a resultant of precalcination thereof.

Fig. 44 shows an XRD pattern of ReS_2 obtained at an S:Re ratio of 9:1 and that of a resultant of precalcination thereof.

Figs. 45A, 45B, 45C, and 45D each show a scanning electron micrograph of ReS_2 resulting from a solvothermal reaction and that of a resultant of precalcination thereof.

Figs. 46A and 46B each show an electron micrograph and an electron diffraction diagram of ReS_2 resulting from a solvothermal reaction at an S:Rh ratio of 9.0:1 and those of a resultant of calcination thereof at 750°C .

Fig. 47 shows the FTIR spectra of a solvothermal product (an S:Rh ratio of 4:1) and a resultant of precalcination thereof at 400°C .

Fig. 48 shows an XRD pattern of ReS_2 synthesized via a hydrothermal reaction at 220°C for 10 hours and that of a resultant of precalcination thereof in an argon stream at 400°C for 5 hours.

Figs. 49A, 49B, 49C, and 49D each show a scanning electron micrograph of ReS_2 resulting from a hydrothermal reaction and a resultant of precalcination thereof.

Fig. 50 shows the results of TEM observation of Rh-Mo-S synthesized via a solvothermal reaction at 220°C for 10 hours.

Fig. 51 shows the oxygen reduction currents of $\text{Rh}_2\text{S}_3/\text{C}$ and Rh-Mo-S/C.

Fig. 52 shows the results of examining the performance as oxygen-reducing catalysts of the fine particle composite comprising fine particles of sulfides or sulfide complexes comprising several elements and conductive fine particles of the present invention.

Fig. 53 shows the results of RDE evaluation of MoRuS/C-1 and MoRuS/C-2, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Fig. 54 shows the results of TEM observation of MoRuS/C-1 synthesized via a solvothermal reaction.

Fig. 55 shows the results of RDE evaluation of MoRuS/C-1, MoRuS/C-4, and MoRuS/C-5, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Fig. 56 shows the results of RDE evaluation of MoRuS/C-5 and Paper, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Fig. 57 shows the results of RDE evaluation of MoRuS/C-11-C2 and MoRuS/C-11-C4, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Fig. 58 shows the results of RDE evaluation of MoRuS/C-12 and MoRuS/C-14, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Fig. 59 shows the results of RDE evaluation of MoRu-H1-CNT-C1 and MoRu-H2-CNT-C1, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Fig. 60 shows the results of TEM observation of MoRu-H1-CNT-C1, which is an Ru-Mo-S product synthesized via a hydrothermal reaction.

Fig. 61 shows the results of RDE evaluation of MoRu-H1-CB-C1 and MoRu-H2-CB-C1, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Fig. 62 shows the results of RDE evaluation of MoRu-H01-CNT-C1, MoRu-H01-CNT-C2, MoRu-H02-CNT-C1, and MoRu-H02-CNT-C2, which are Ru-Mo-S products synthesized via a hydrothermal reaction.

Fig. 63 shows the results of RDE evaluation of MoRu-S01-CNT-C1, MoRu-S01-CNT-C2, MoRu-S02-CNT-C1, and MoRu-S02-CNT-C2, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Best Modes for Carrying out the Invention

Objectives of the present examples are to synthesize a fine particle composite comprising fine particles of MoS_2 , RuS_2 , Rh_2S_3 , or ReS_2 and conductive fine particles via a hydrothermal or solvothermal reaction, to explore the possibility of a fine particle composite comprising fine particles of a binary or ternary sulfide solid solution and conductive fine particles, and to establish applications of such fine particle composite comprising fine particles of a sulfide or sulfide complex and conductive fine particles as

a catalyst used for a fuel cell.

Fig. 1 shows a flow chart detailing the method of synthesis via a hydrothermal or solvothermal reaction of the present invention. A Teflon-lined autoclave was used for a low-temperature reaction, and a Hastelloy-C-lined autoclave was used for a high-temperature reaction. The reaction was carried out *in situ*. Specific conditions for synthesis are described below.

The conditions are as shown in Fig. 1.

(1) Starting materials (Mo, Ru, Rh, Re, and S) are introduced into an autoclave. The types and the quantitative ratio of starting materials are determined.

(2) A solvent is introduced into an autoclave. The type and the amount of the solvent are determined.

(3) A hydrothermal or solvothermal reaction is carried out.

(4) A solid product is washed, recovered with the use of a centrifuger, and then dried *in vacuo*.

(5) Precalcination is carried out in an inert gas atmosphere, such as Ar. The temperature and the duration are determined.

(6) Properties are evaluated by means of SEM, HRTEM, EDX, FTIR, XRD, or other means.

Example 1: Synthesis of MoS₂

Mo(CO)₆, MoCl₅, (NH₄)₆Mo₇O₂₄·4H₂O, and (NH₄)₃[PO₄Mo₁₂O]·3H₂O were used as starting materials for Mo, S (solid sulfur) and thiourea ((NH₂)₂CS) were used as starting materials for S, and xylene or distilled water was used as a solvent. A solvothermal or hydrothermal reaction was carried out at 220°C or 350°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 350°C to 750°C for 5 hours.

1.1: Synthesis of MoS₂ via solvothermal reaction

When Mo(CO)₆ and S were used as starting materials for the solvothermal reaction, well-dispersed MoS₂ powder was obtained. MoS₂ powder that had been synthesized at a low temperature of 220°C for 10 hours had low crystallinity, although

crystallinity was improved via precalcination in an argon atmosphere at 350°C. By synthesizing the powder at a high temperature of 350°C for 10 hours, the crystallinity of the resulting powder was improved, compared with the powder synthesized at a low temperature.

1.1.1: Influence imposed by starting materials for Mo

A synthesis experiment was performed using Mo(CO)_6 or MoCl_5 as a starting material for Mo at 220°C for 10 hours. When using MoCl_5 as a starting material, the resulting MoS_2 powder had somewhat higher crystallinity, and particles were more firmly aggregated. Thus, Mo(CO)_6 was employed as a starting material for Mo.

Fig. 2 shows an XRD pattern of MoS_2 synthesized via a solvothermal reaction, with the solvent being xylene, the temperature being 220°C, and the duration being 10 hours. In the figure, "a" represents MoCl_5+S and "b" represents $\text{Mo(CO)}_6+\text{S}$.

Fig. 3 shows an SEM photograph of MoS_2 powder synthesized from MoCl_5 precalcined at 400°C for 5 hours.

1.1.2: Influence imposed by starting materials for S

A synthesis experiment was performed using S or thiourea as a starting material for sulfur at 220°C for 10 hours. The resulting MoS_2 powder had somewhat higher crystallinity when synthesized from S. In contrast, the resultant became firmly aggregated when thiourea was used as a starting material. Thus, S was employed as a sulfur source.

Fig. 4 shows an XRD pattern of MoS_2 synthesized via a solvothermal reaction, with the solvent being xylene, the temperature being 220°C, and the duration being 10 hours. In the figure, "a" represents $\text{Mo(CO)}_6+\text{thiourea}$, and "b" represents $\text{Mo(CO)}_6+\text{S}$.

Fig. 5 shows an SEM photograph of MoS_2 powder synthesized from thiourea precalcined at 400°C for 5 hours.

1.1.3: Effects of precalcination

MoS_2 synthesized from Mo(CO)_6 and S via a solvothermal reaction at 220°C for 10 hours was precalcined in an Ar stream. Fig. 6 shows XRD patterns of MoS_2 synthesized via a solvothermal reaction (a) and resultant of precalcination thereof (b, c);

wherein "b" represents 350°C for 2 hours and "c" represents 600°C for 2 hours.

As shown in Fig. 6, crystallinity was increased via precalcination at 350°C, and crystallinity attained via precalcination at 600°C was not very different from that attained at 350°C. Thus, it was determined that precalcination would be carried out at 400°C or higher for 5 hours in the following experiments.

1.1.4: Influence imposed by S:Mo ratio

When synthesizing MoS₂ from Mo(CO)₆ and S via a solvothermal reaction at 220°C for 10 hours, the S:Mo ratios of the starting materials were varied. Fig. 7 shows XRD patterns of MoS₂ products synthesized from Mo(CO)₆ and S via a solvothermal reaction at 220°C for 10 hours while varying S:Mo ratios. Also, Fig. 8 shows XRD patterns of a resultant of precalcination of MoS₂ at 400°C for 5 hours synthesized from Mo(CO)₆ and S via a solvothermal reaction at 220°C for 10 hours while varying S:Mo ratios. In these figures, "a" represents an S:Mo ratio of 1.6:1, "b" represents a ratio of 2.0:1, "c" represents a ratio of 2.4:1, and "d" represents a ratio of 3.0:1.

As shown in Fig. 7 and in Fig. 8, the resulting product had a monolayer structure of MoS₂, even when the S:Mo ratio was varied from 1.6:1 to 3.0:1. When the S:Mo ratio was 2.0:1 or higher, the crystallinity of MoS₂ was somewhat increased. No difference was observed in the crystallinity of products precalcined at 400°C for 5 hours in an argon stream.

1.1.5: Microscopic observation of MoS₂

MoS₂ synthesized from Mo(CO)₆ and S via a solvothermal reaction at 220°C for 10 hours at an S:Mo ratio of 2.4:1 and a resultant of precalcination thereof at 400°C for 5 hours were observed under an electron microscope. Fig. 9A shows a scanning electron micrograph of MoS₂ resulting from a solvothermal reaction, and Fig. 9B shows that of a resultant of precalcination thereof at 400°C for 5 hours. Fig. 10 shows a transmission electron micrograph of a resultant of precalcination, at 400°C for 5 hours, of MoS₂ resulting from a solvothermal reaction. The resulting MoS₂ was found to be composed of well-dispersed fine particles of about 100 nm, which was significantly different from MoS₂ synthesized from other Mo starting materials shown in Figs. 3A, 3B, 5A, and 5B.

In particular, enhanced aggregation was not observed as a result of precalcination.

As a result of transmission electron microscopic observation, the product was found to have a fine structure of multiple layers of fibers. The XRD pattern of the resultant may be different from that described in the JCPDS card in terms of diffraction intensities, because of such structure.

1.1.6: Synthesis at high temperature

Synthesis of MoS_2 from Mo(CO)_6 and S via a solvothermal reaction at a higher temperature of 350°C for 10 hours was attempted while varying the S:Mo ratio. Fig. 11 shows an XRD pattern of MoS_2 resulting from a solvothermal reaction. Also, Figs. 12A and 12B each show an electron micrograph of MoS_2 resulting from a solvothermal reaction.

By raising the reaction temperature, crystallinity of the resulting MoS_2 was improved to a level equivalent to that attained via precalcination. When the S:Mo ratio was particularly high, the diffraction intensity of (002) was increased.

As a result of scanning electron microscopic observation, the configuration of the product was found to be the same as the configuration resulting from a low-temperature reaction, and it was found to be composed of fine particles. As a result of transmission electron microscopic observation, two components, i.e., a fibrous layer having a strong contrast and a lattice layer having relatively high crystallinity, were observed. The lattice intervals were found to be $6.2 \text{ \AA}$ and $2.7 \text{ \AA}$, which were considered to correspond to $\langle 002 \rangle$ and $\langle 100 \rangle$ of MoS_2 .

It was thus demonstrated that MoS_2 with high crystallinity and excellent dispersibility could be synthesized via a solvothermal reaction using Mo(CO)_6 and S as starting materials at an S:Mo ratio of 3:1 at 350°C for 10 hours.

1.2: Synthesis of MoS_2 via hydrothermal reaction

Synthesis of MoS_2 was attempted via a hydrothermal reaction using MoCl_5 , $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$, and $(\text{NH}_4)_3[\text{PO}_4\text{Mo}_{12}\text{O}] \cdot 3\text{H}_2\text{O}$ as starting materials for Mo and thiourea $(\text{NH}_2)_2\text{CS}$ as a starting material for S. As a result, MoS_2 having higher crystallinity than the crystallinity attained via a solvothermal reaction was obtained.

When sodium hydroxide was added to MoCl_5 , MoS_2 composed of fine particles having relatively high dispersibility was obtained with the use of $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ or $(\text{NH}_4)_3[\text{PO}_4\text{Mo}_{12}\text{O}] \cdot 3\text{H}_2\text{O}$ as a starting material.

1.2.1: Reaction between MoCl_5 and thiourea with the addition of ammonia

Synthesis of MoS_2 was attempted using MoCl_5 and thiourea as starting materials while varying the quantitative ratio thereof and varying the amount of ammonia to be added at 220°C for 10 hours. Fig. 13 shows an XRD pattern of MoS_2 hydrothermally synthesized at 220°C for 10 hours with the addition of ammonia. Fig. 14 shows an XRD pattern of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of MoS_2 hydrothermally synthesized with the addition of ammonia. In these figures, "a" represents an S:Mo ratio of 2.2:1 without the addition of ammonia, "b" represents an S:Mo ratio of 2.2:1 in the presence of 50% of ammonia by volume, "c" represents an S:Mo ratio of 3.0:1 in the presence of 50% of ammonia by volume, and "d" represents an S:Mo ratio of 4.0:1 in the presence of 50% of ammonia by volume. Further, Figs. 15A and 15B each show a scanning electron micrograph of MoS_2 (an S:Mo ratio of 2.2:1) hydrothermally synthesized at 220°C for 10 hours with the addition of ammonia.

When the S:Mo ratio was 30:1, a product exhibiting a deviated diffraction line (002) was obtained, regardless of the presence or absence of ammonia. When this product was precalcined at 400°C , the same diffraction pattern as that of conventional MoS_2 was obtained. When the S:Mo ratio was 30:1, some sorts of substances may have been introduced into sites between layers. Precalcination resulted in improved crystallinity. In general, the product was firmly aggregated.

1.2.2: Reaction between MoCl_5 and thiourea with the addition of sodium hydroxide

Fig. 16 shows an XRD pattern of MoS_2 hydrothermally synthesized at 220°C for 10 hours with the addition of sodium hydroxide at an S:Mo ratio of 2.2:1 and that of MoS_2 precalcined at 400°C for 5 hours in an argon stream. In the figure, "a" represents an aqueous 0.6 M NaOH solution, "b" represents an aqueous 0.9 M NaOH solution, "c" represents an aqueous 1.2 M NaOH solution, and "d" represents an aqueous 1.8 M NaOH solution. Fig. 17 shows a scanning electron micrograph of MoS_2 hydrothermally

synthesized at 220°C for 10 hours in an aqueous 0.6M NaOH solution (an S:Mo ratio of 2.2:1).

MoS₂ synthesized with the addition of sodium hydroxide had relatively high crystallinity and was composed of well-dispersed fine spherical particles.

1.2.3: Reaction between (NH₄)₃[PO₄Mo₁₂O]·3H₂O and thiourea

Fig. 18 shows an XRD pattern of a resultant of a hydrothermal reaction of (NH₄)₃[PO₄Mo₁₂O]·3H₂O and thiourea and that of a resultant of precalcination thereof. Figs. 19A and 19B each show a scanning electron micrograph of a resultant of a hydrothermal reaction of (NH₄)₃[PO₄Mo₁₂O]·3H₂O and thiourea and that of a resultant of precalcination thereof. Fig. 20 shows the FTIR spectra of a resultant of a hydrothermal reaction of (NH₄)₃[PO₄Mo₁₂O]·3H₂O and thiourea and that of a resultant of precalcination thereof. In these figures, "a" represents a product hydrothermally synthesized at 220°C for 10 hours and "b" represents a product calcined at 400°C for 5 hours.

The resulting product had high crystallinity, and crystallinity was not improved via precalcination. The sample was composed of fine particles having relatively high dispersibility. The FTIR spectra did not show any absorption resulting from organic matter.

1.2.4: Reaction between (NH₄)₆Mo₇O₂₄·4H₂O and thiourea

Fig. 21 shows an XRD pattern of a resultant of a hydrothermal reaction of (NH₄)₆Mo₇O₂₄·4H₂O and thiourea and that of a resultant of precalcination thereof. Figs. 22A and 22B each show a scanning electron micrograph of a resultant of a hydrothermal reaction of (NH₄)₆Mo₇O₂₄·4H₂O and thiourea and that of a resultant of precalcination thereof. Fig. 22A shows a product hydrothermally synthesized at 220°C for 10 hours, and Fig. 22B shows a product calcined in argon at 400°C for 5 hours. Fig. 23 shows the FTIR spectra of a resultant of a hydrothermal reaction of (NH₄)₆Mo₇O₂₄·4H₂O and thiourea and that of a resultant of precalcination thereof. In these figures, "a" represents a product hydrothermally synthesized at 220°C for 10 hours and "b" represents a product calcined in argon at 400°C for 5 hours.

The results attained with the use of $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ as a starting material were the same as those attained with the use of $(\text{NH}_4)_3[\text{PO}_4\text{Mo}_{12}\text{O}] \cdot 3\text{H}_2\text{O}$ as a starting material. The resulting product had high crystallinity, and crystallinity was not improved via precalcination. The sample was composed of fine particles having relatively high dispersibility. The FTIR spectra did not show any absorption resulting from organic matter.

Example 2: Synthesis of RuS_2

$\text{Ru}(\text{CO})_{12}$ was used as a starting material for Ru, S (solid sulfur) was used as a starting material for S, and xylene or distilled water was used as a solvent. A solvothermal or hydrothermal reaction was carried out at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 400°C for 5 hours.

2.1: Synthesis of RuS_2 via solvothermal reaction

Fig. 24 shows an XRD pattern of RuS_2 synthesized via a solvothermal reaction at 220°C for 10 hours while varying S:Ru ratios. In the figure, "a" represents an S:Ru ratio of 6:1, and "b" represents an S:Ru ratio of 4:1. Regardless of the S:Ru ratio, the product exhibited low crystallinity. The FTIR spectra of RuS_2 synthesized via a solvothermal reaction at 220°C for 10 hours and a resultant of precalcination thereof shown in Fig. 28 demonstrate that the resultant of a solvothermal reaction contains organic matter. In the figure, "a" represents resulting RuS_2 , and "b" represents a resultant of precalcination thereof.

Fig. 25 shows an XRD pattern of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of RuS_2 synthesized via a solvothermal reaction at 220°C for 10 hours. In the figure, "a" represents an S:Ru ratio of 6:1, "b" represents an S:Ru ratio of 4:1, "c" represents an S:Ru ratio of 4.8:1, "d" represents an S:Ru ratio of 4.3:1, and "e" represents an S:Ru ratio of 4:1. Organic matter in the product was eliminated via precalcination. An S:Ru ratio of 4.8:1 or smaller was found to be necessary, so as to significantly change behavior because of S:Ru ratios and to cause crystallization via precalcination of a sample. When the S:Ru ratio was lowered to 4:1, crystallization was significantly advanced, and generation of an Ru metal also became observable.

Figs. 26A, 26B, and 26C each show a scanning electron micrograph of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of RuS₂ synthesized via a solvothermal reaction at 220°C for 10 hours. In the figure, "a" represents an S:Ru ratio of 4:1, "b" represents an S:Ru ratio of 4.3:1, and "c" represents an S:Ru ratio of 6:1. Spherical particles of about 1 μm were aggregated, and the S:Ru ratio did not significantly influence powder or particle configurations. Transmission electron micrographs of a resultant of precalcination of RuS₂ shown in Figs. 27A, 27B, 27C, and 27D demonstrate that precalcined spherical particles were fine particles and that each particle exhibits a lattice image, indicating satisfactory crystallization.

Fig. 28 shows the FTIR spectra of RuS₂ synthesized via a solvothermal reaction (with an S:Ru ratio of 4:1) and that of a resultant of precalcination thereof at 400°C. In the figure, "a" represents a product of hydrothermal synthesis, and "b" represents a resultant of precalcination thereof.

2.2: Synthesis of RuS₂ via hydrothermal reaction

Fig. 29 shows an XRD pattern of RuS₂ resulting from a hydrothermal reaction at 220°C for 10 hours. Fig. 30 shows an XRD pattern of a resultant of precalcination, at 400°C for 5 hours, of RuS₂ resulting from a hydrothermal reaction at 220°C for 10 hours. In these figures, "a" represents an S:Ru ratio of 2:1, "b" represents an S:Ru ratio of 2.8:1, "c" represents an S:Ru ratio of 3.6:1, and "d" represents an S:Ru ratio of 4.4:1. Further, Figs. 31A and 31B each show a scanning electron micrograph of RuS₂ and that of a resultant of precalcination thereof. Fig. 31A shows a product, RuS₂, attained at an S:Ru ratio of 4.4:1, and Fig. 31B shows a resultant of precalcination thereof at 400°C for 5 hours.

At an S:Ru ratio of 3.6:1 or lower, a crystal phase was generated in the resulting product, although a phase could not be identified. This phase is considered to contain organic matter. The non-crystalline phase attained at an S:Ru ratio of 4.4:1 became crystallized into RuS₂ via precalcination. At an S:Ru ratio of 2.8:1 or lower, an unidentified phase was also observed in a resultant of precalcination. At an S:Ru ratio of 2.0:1, generation of an Ru metal was observed.

Example 3: Synthesis of Rh_2S_3

$\text{Rh}_6(\text{CO})_{16}$ was used as a starting material for Rh, S (solid sulfur) was used as a starting material for S, and xylene or distilled water was used as a solvent. A solvothermal or hydrothermal reaction was carried out at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 400°C for 5 hours (partially at 750°C).

3.1: Synthesis of Rh_2S_3 via solvothermal reaction

Fig. 32 shows an XRD pattern of Rh_2S_3 synthesized via a solvothermal reaction at 220°C for 10 hours. Fig. 33 shows an XRD pattern of a resultant of precalcination, in an argon stream at 400°C for 5 hours, of Rh_2S_3 synthesized via a solvothermal reaction at 220°C for 10 hours. In these figures, "a" represents an S:Rh ratio of 1.5:1, "b" represents an S:Rh ratio of 3.6:1, and "c" represents an S:Rh ratio of 5.0:1. Fig. 34 shows an XRD pattern of Rh_2S_3 synthesized via a solvothermal reaction at 220°C for 10 hours at an S:Rh ratio of 5.0:1 and that of a resultant of precalcination thereof in an Ar stream at 400°C for 5 hours and at 750°C for 5 hours. In the figure, "a" represents a product, Rh_2S_3 , of a solvothermal reaction, "b" represents a resultant of precalcination thereof in an Ar stream at 400°C for 5 hours, and "c" represents a resultant of precalcination thereof in an Ar stream at 750°C for 5 hours.

A product of a solvothermal reaction, Rh_2S_3 , exhibited low crystallinity; however, crystallization was remarkably advanced via precalcination thereof. Crystallization resulting from precalcination is influenced by the S:Rh ratio. At an S:Rh ratio of 3.6:1 or lower, crystallization occurred; however, crystallization did not occur at an S:Rh ratio of 5.0:1. By raising the precalcination temperature to 750°C , the sample became crystallized at an S:Rh ratio of 5:1.

Figs. 35A, 35B, 35C, and 35D each show a scanning electron micrograph of Rh_2S_3 resulting from a solvothermal reaction and a resultant of precalcination thereof. In the figures, "a" represents a product of a solvothermal reaction attained at an S:Rh ratio of 3.6:1, "b" represents a resultant of calcination thereof at 400°C , "c" represents a product of a solvothermal reaction attained at an S:Rh ratio of 5.0:1, and "d" represents a

resultant of calcination thereof at 400°C. The products were composed of very fine particles, regardless of the S:Rh ratio, and no change was observed via precalcination.

3.2: Synthesis of Rh_2S_3 via hydrothermal reaction

Fig. 36 shows an XRD pattern of Rh_2S_3 resulting from a hydrothermal reaction and that of a resultant of precalcination thereof. In the figure, "a" represents a product of a hydrothermal reaction attained at an S:Rh ratio of 1.5:1, "b" represents a resultant of calcination thereof at 400°C, "c" represents a product of a hydrothermal reaction attained at an S:Rh ratio of 3.0:1, and "d" represents a resultant of calcination thereof at 400°C.

A product of a hydrothermal reaction, Rh_2S_3 , exhibited low crystallinity, regardless of the S:Rh ratio; however, crystallization was remarkably advanced via precalcination. At an S:Rh ratio of 1.5:1, a resultant of precalcination contained impurities, and a phase of interest was more likely to be obtained at an S:Rh ratio of 3.0:1.

Figs. 37A and 37B each show an electron micrograph of Rh_2S_3 resulting from a hydrothermal reaction and that of a resultant of precalcination thereof. In the figures, "a" represents a resultant of calcination at 400°C of a product of a hydrothermal reaction at an S:Rh ratio of 1.5:1, and "b" represents a resultant of calcination at 400°C of a product of a hydrothermal reaction at an S:Rh ratio of 3.0:1. The product of the hydrothermal reaction was partially idiomorphic and grown to become a larger crystal. While the XRD pattern exhibits noncrystalline properties, the crystal assuredly grew, which is an inexplicable phenomenon.

Figs. 38A and 38B each show an electron micrograph and an electron diffraction diagram of Rh_2S_3 resulting from a hydrothermal reaction at an S:Rh ratio of 3.0:1. Figs. 39A and 39B each show an electron micrograph and an electron diffraction diagram of a resultant of calcination at 400°C of Rh_2S_3 resulting from a hydrothermal reaction at an S:Rh ratio of 3.0:1. Growth of crystals described above was verified by the transmission electron micrograph or the electron diffraction diagram shown in Figs. 38A, 38B, 39A, and 39B.

Fig. 40 shows the FTIR spectra of hydrothermally synthesized Rh_2S_3 (with an

S:Rh ratio of 3:1) and a resultant of precalcination thereof at 400°C. In the figure, “a” represents a product of hydrothermal synthesis, and “b” represents a resultant of precalcination thereof. The IR spectra shown in Fig. 40 demonstrate that the product of the hydrothermal reaction did not contain any organic matter.

Example 4: Synthesis of ReS₂

Re₂(CO)₁₀ was used as a starting material for Re, S (solid sulfur) was used as a starting material for S, and xylene or distilled water was used as a solvent. A solvothermal or hydrothermal reaction was carried out at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 400°C or 750°C for 5 hours.

4.1: Synthesis of ReS₂ via solvothermal reaction

Fig. 41 shows an XRD pattern of ReS₂ synthesized via a solvothermal reaction at 220°C for 10 hours. Fig. 42 shows an XRD pattern of a resultant of precalcination in an Ar stream at 400°C for 5 hours of ReS₂ synthesized via a solvothermal reaction at 220°C for 10 hours. In the figures, "a" represents an S:Re ratio of 1.32:1, "b" represents an S:Re ratio of 2:1, "c" represents an S:Re ratio of 4:1, and "d" represents an S:Re ratio of 9:1.

When the S:Re ratio was lower than 2:1, a very sharp diffraction line was observed in addition to a broad diffraction line obtained from a low-crystalline substance, although this sharp line could not be identified. Since this diffraction line disappears upon precalcination, this line is considered to be derived from organic matter. When a sample was precalcined at 400°C and the S:Re ratio was lower than 2:1, a diffraction line at around 40° did not separate at all, and the behavior was different from that of a sample with a higher S:Re ratio.

Fig. 43 shows an XRD pattern of ReS₂ obtained at an S:Re ratio of 4:1 and that of a resultant of precalcination thereof. In the figure, "a" represents a product, ReS₂, of a solvothermal reaction, "b" represents a resultant of precalcination thereof at 400°C, and "c" represents a resultant of precalcination thereof at 750°C. Fig. 44 shows an XRD pattern of ReS₂ obtained at an S:Re ratio of 9:1 and that of a resultant of

precalcination thereof. In the figure, "a" represents a product, ReS_2 , of a solvothermal reaction, "b" represents a resultant of precalcination thereof at 400°C , and "c" represents a resultant of precalcination thereof at 750°C . Crystallinity is enhanced via calcination at 750°C ; however, the diffraction line remains broad and the sample is not considered to be completely crystallized.

Figs. 45A, 45B, 45C, and 45D each show a scanning electron micrograph of ReS_2 resulting from a solvothermal reaction and that of a resultant of precalcination thereof. In the figures, "a" represents a product of a solvothermal reaction at an S:Re ratio of 4:1, "b" represents a resultant of precalcination thereof at 400°C , "c" represents a product of a solvothermal reaction at an S:Re ratio of 2:1, and "d" represents a resultant of precalcination thereof at 400°C . The resultant was composed of spherical particles. When the S:Re ratio was 2:1, in particular, the size was homogeneous. When the S:Re ratio was 4:1, however, the particle diameter distribution became broadened.

Figs. 46A and 46B each show an electron micrograph and an electron diffraction diagram of ReS_2 resulting from a solvothermal reaction at an S:Rh ratio of 9.0:1 and those of a resultant of calcination thereof at 750°C .

Fig. 47 shows the FTIR spectra of a solvothermal product (with an S:Rh ratio of 4:1) and a resultant of precalcination thereof at 400°C . In the figure, "a" represents a product of hydrothermal synthesis and "b" represents a resultant of precalcination thereof.

Table 1 shows the results of EDX analysis of resultants of precalcination at 750°C .

Table 1

Area No.	S:Re
1	2.39
2	1.80
3	1.21
4	2.19
5	1.71
6	1.26
7	2.19
8	2.22
9	1.99

As a result of EDX analysis of compositions, an S:Re ratio of 1.98:1 was attained as a mean, and variation in composition was observed regarding the same spherical particle. Thus, an accurate composition ratio may not necessarily be attained.

4.2: Synthesis of ReS₂ via hydrothermal reaction

Fig. 48 shows an XRD pattern of ReS₂ synthesized via a hydrothermal reaction at 220°C for 10 hours and that of a resultant of precalcination thereof in an Ar stream at 400°C for 5 hours. In the figure, "a" represents a product attained at an S:Re ratio of 2:1, "b" represents a resultant of precalcination thereof, "c" represents a product attained at an S:Re ratio of 4:1, and "d" represents a resultant of precalcination thereof.

Even when the S:Re ratio was changed to 2:1 or 4:1 and the sample was precalcined at 400°C, crystallinity was somewhat improved, but the crystallinity of the product remained low.

Figs. 49A, 49B, 49C, and 49D each show a scanning electron micrograph of ReS₂ resulting from a hydrothermal reaction and a resultant of precalcination thereof. In the figures, "a" represents a product of a hydrothermal reaction at an S:Re ratio of 4:1, "b" represents a resultant of precalcination thereof at 400°C, "c" represents a product of a hydrothermal reaction at an S:Re ratio of 2:1, and "d" represents a resultant of precalcination thereof at 400°C. The product was firmly aggregated.

Example 5: Synthesis of Rh-Mo-S

Rh₆(CO)₁₆ was used as a starting material for Rh, (NH₄)₆Mo₇O₂₄·4H₂O was used

as a starting material for Mo, S (solid sulfur) was used as a starting material for S, and xylene was used as a solvent. A solvothermal reaction was carried out at 400°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 400°C for 5 hours.

As a result of synthesis, the product exhibited an Mo:Rh ratio of 0.2: 0.8, an S:Rh ratio of 2.25:1, an S:Mo ratio of 3.0:1, and a filling rate of 50%.

Fig. 50 shows the results of TEM observation of Rh-Mo-S synthesized via a solvothermal reaction at 220°C for 10 hours. The results of TEM/EDX analysis demonstrate that Rh-Mo-S is composed of 42.68% of Rh, 4.86% of Mo, and 52.46% of S in terms of an atomic percentage on average. The results also demonstrate that the Mo:Rh ratio is 0.10:0.90, the S/Rh ratio is 1.34:1, and the S:Mo ratio is 12.85:1.

Electrochemical properties of Rh₂S₃/C and Rh-Mo-S/C

As electrochemical properties of Rh₂S₃/C obtained in Example 3 and those of Rh-Mo-S/C obtained in Example 5, the oxygen reduction currents in relation to electric potentials were inspected.

Fig. 51 shows the oxygen reduction currents of Rh₂S₃/C and Rh-Mo-S/C. In Fig. 50, enlarged views of the area around the potential at which oxygen reduction is initiated were additionally provided.

The results shown in Fig. 51 demonstrate oxygen-reducing functions of Rh₂S₃/C and Rh-Mo-S/C. While the activity of Rh₂S₃/C is 5.76 E-06 at 0.7 V, the activity of Rh-Mo-S/C is approximately 5 times greater; i.e., 2.52E-05.

Performance evaluation

Fig. 52 shows the results of examining the performance as an oxygen-reducing catalyst of the fine particle composite comprising fine particles of sulfides or sulfide complexes comprising several elements and conductive fine particles of the present invention. The results shown in Fig. 52 demonstrate that the fine particle composite comprising fine particles of a sulfide or sulfide composite and conductive particles of the present invention is excellent in oxygen reducing catalytic activity.

Dispersion state of Rh₂S₃/C and Rh-Mo-S/C

$\text{Rh}_2\text{S}_3/\text{C}$ was synthesized in the following manner. At an S:Rh ratio of 1.65:1 and a C: Rh_2S_3 ratio of 4:8, a solvothermal reaction was conducted using xylene as a solvent at 400°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 400°C for 5 hours. Also, Rh-Mo-S/C was synthesized in the following manner. At an Mo:Rh ratio of 5:95, an S:Rh ratio of 1.65:1, and a C:(Mo+Rh) $_2\text{S}_3$ ratio of 4:8, a solvothermal reaction was conducted using xylene as a solvent at 400°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 400°C for 5 hours.

Synthesized powder was introduced into alcohol and the resultant was subjected to ultrasonic dispersion for about 5 minutes. The resulting slurry was added dropwise to the Cu microgrid, dried naturally, and then subjected to FE-TEM observation as an observation sample under a field-emission analytical electron microscope (“Tecnai” G2-F20-MAT, manufactured by FE; accelerating voltage: 200 kV (max.); resolution: 0.24 nm (irradiation on the axis)).

As a result of FE-TEM observation, Rh and S were found to be dispersed at substantially the same positions in $\text{Rh}_2\text{S}_3/\text{C}$. Thus, $\text{Rh}_2\text{S}_3/\text{C}$ was determined to be a product of synthesis. C particles are extensively dispersed, so as to surround the sites at which Rh and S are detected. In Rh-Mo-S/C, Rh, Mo, and S particles are dispersed at substantially the same positions. Thus, Rh-Mo-S/C is determined to be a product of synthesis. Also, C particles are extensively dispersed, so as to surround the sites at which Rh, Mo, and S are detected.

Example 6: Synthesis of Ru-Mo-S

6.1: Ratio of Mo:Ru synthesis

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, Ketjen Black EC300J (tradename) was used as carbon black, and xylene was used as a solvent. A solvothermal reaction was carried out at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 600°C for 5 hours.

As a result of synthesis, a product comprising Mo and Rh at a ratio of 0.2: 0.8

(this product is referred to as “MoRuS/C-1”) and a product comprising Mo and Rh at a ratio of 0.05:0.95 (this product is referred to as “MoRuS/C-2”) were obtained.

Fig. 53 shows the results of RDE evaluation of MoRuS/C-1 and MoRuS/C-2, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Fig. 54 shows the results of TEM observation of MoRuS/C-1 via a solvothermal reaction. The results shown in Fig. 54 demonstrate that MoRuS and C are dispersed on a nanoscale level.

6.2: S content

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, Ketjen Black EC300J (tradename) was used as carbon black, and xylene was used as a solvent. A solvothermal reaction was carried out at an Mo:Rh ratio of 0.2:0.8 at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 600°C for 5 hours.

As a result of synthesis, a product with an S content of 300% (this product is referred to as “MoRuS/C-1”), a product with an S content of 100% (this product is referred to as “MoRuS/C-4”), and a product with an S content of 70% (this product is referred to as “MoRuS/C-5”) were obtained.

Fig. 55 shows the results of RDE evaluation of MoRuS/C-1, MoRuS/C-4, and MoRuS/C-5, which are Ru-Mo-S products synthesized via a solvothermal reaction.

6.3: Carbon black (CB) and carbon nanotube (CNT) paper

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, carbon black (Ketjen Black EC300J, tradename) or carbon nanotube (CNT) paper was used, and xylene was used as a solvent. A solvothermal reaction was carried out at an Mo:Rh ratio of 0.2:0.8 at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 600°C for 5 hours.

As a result of synthesis, carbon black (referred to as “MoRuS/C-5”) and carbon nanotube (CNT) paper (referred to as “Paper”) were obtained.

Fig. 56 shows the results of RDE evaluation of MoRuS/C-5 and Paper, which are

Ru-Mo-S products synthesized via a solvothermal reaction.

6.4: Calcination temperature

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, Ketjen Black EC300J (tradename) was used as carbon black, and xylene was used as a solvent. A solvothermal reaction was carried out at an Mo:Rh ratio of 0.21:0.79 at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 350°C for 5 hours or at 450°C for 5 hours.

As a result of synthesis, a product attained at 350°C for 5 hours (this product is referred to as “MoRuS/C-11-C2”) and a product attained at 450°C for 5 hours (this product is referred to as “MoRuS/C-11-C4”) were obtained.

Fig. 57 shows the results of RDE evaluation of MoRuS/C-11-C2 and MoRuS/C-11-C4, which are Ru-Mo-S products synthesized via a solvothermal reaction.

6.5: Calcination time

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, Ketjen Black EC300J (tradename) was used as carbon black, and xylene was used as a solvent. A solvothermal reaction was carried out at an Mo:Rh ratio of 0.21:0.79 at 140°C for 20 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 350°C for 2 hours or at 350°C for 5 hours.

As a result of synthesis, a product attained at 350°C for 2 hours (this product is referred to as “MoRuS/C-12”) and a product attained at 350°C for 5 hours (this product is referred to as “MoRuS/C-14”) were obtained.

Fig. 58 shows the results of RDE evaluation of MoRuS/C-12 and MoRuS/C-14, which are Ru-Mo-S products synthesized via a solvothermal reaction.

6.6: Changing of synthesis conditions using carbon nanotube (CNT) dispersion

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, a dispersion of 0.05 g of carbon nanotubes (CNT) in water was used, and water was used as a solvent.

A hydrothermal reaction was carried out at an Mo:Rh ratio of 0.17:0.83 at 140°C for 10 hours or at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 350°C for 2 hours.

As a result of synthesis, a product attained at 140°C for 10 hours (this product is referred to as “MoRu-H1-CNT-C1”) and a product attained at 220°C for 10 hours (this product is referred to as “MoRu-H2-CNT-C1”) were obtained.

Fig. 59 shows the results of RDE evaluation of MoRu-H1-CNT-C1 and MoRu-H2-CNT-C1, which are Ru-Mo-S products synthesized via a hydrothermal reaction.

Fig. 60 shows the results of TEM observation of MoRu-H1-CNT-C1, which is an Ru-Mo-S product synthesized via a hydrothermal reaction. The results shown in Fig. 60 demonstrate that MoRuS are dispersed on carbon nanotubes on a nanoscale level.

6.7: Changing of synthesis conditions using carbon black (CB)

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, Ketjen Black EC300J (tradename) was used as carbon black, and xylene was used as a solvent. A solvothermal reaction was carried out at an Mo:Rh ratio of 0.17:0.83 at 140°C for 10 hours or at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 350°C for 2 hours.

As a result of synthesis, a product attained at 140°C for 10 hours (this product is referred to as “MoRu-H1-CB-C1”) and a product attained at 220°C for 10 hours (this product is referred to as “MoRu-H2-CB-C1”) were obtained.

Fig. 61 shows the results of RDE evaluation of MoRu-H1-CB-C1 and MoRu-H2-CB-C1, which are Ru-Mo-S products synthesized via a solvothermal reaction.

6.8: Changing of S content and calcination temperature using a dispersion of carbon nanotubes (CNT) in water

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, a dispersion of 0.2 g of carbon nanotubes (CNT) in water was used, and water was used as a solvent. A

hydrothermal reaction was carried out at an Mo:Rh ratio of 0.2:0.9 at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 350°C for 2 hours or at 550°C for 2 hours.

As a result of synthesis, a product attained at 350°C for 2 hours with an S content of 70% (this product is referred to as “MoRu-H01-CNT-C1”), a product attained at 550°C for 2 hours with an S content of 70% (this product is referred to as “MoRu-H01-CNT-C2”), a product attained at 350°C for 2 hours with an S content of 50% (this product is referred to as “MoRu-H02-CNT-C1”), and a product attained at 550°C for 2 hours with an S content of 50% (this product is referred to as “MoRu-H02-CNT-C2”) were obtained.

Fig. 62 shows the results of RDE evaluation of MoRu-H01-CNT-C1, MoRu-H01-CNT-C2, MoRu-H02-CNT-C1, and MoRu-H02-CNT-C2, which are Ru-Mo-S products synthesized via a hydrothermal reaction.

6.9: Changing of S content and calcination temperature using a dispersion of carbon nanotubes (CNT) in xylene

$\text{Ru}_3(\text{CO})_{16}$ was used as a starting material for Ru, MoCO_6 was used as a starting material for Mo, S (solid sulfur) was used as a starting material for S, a dispersion of 0.2 g of carbon nanotubes (CNT) in xylene was used, and xylene was used as a solvent. A solvothermal reaction was carried out at an Mo:Rh ratio of 0.2:0.9 at 220°C for 10 hours. Thereafter, precalcination was carried out in an Ar atmosphere at 350°C for 2 hours or at 550°C for 2 hours.

As a result of synthesis, a product attained at 350°C for 2 hours with an S content of 70% (this product is referred to as “MoRu-S01-CNT-C1”), a product attained at 550°C for 2 hours with an S content of 70% (this product is referred to as “MoRu-S01-CNT-C2”), a product attained at 350°C for 2 hours with an S content of 50% (this product is referred to as “MoRu-S02-CNT-C1”), and a product attained at 550°C for 2 hours with an S content of 50% (this product is referred to as “MoRu-S02-CNT-C2”) were obtained.

Fig. 63 shows the results of RDE evaluation of MoRu-S01-CNT-C1,

MoRu-S01-CNT-C2, MoRu-S02-CNT-C1, and MoRu-S02-CNT-C2, which are Ru-Mo-S products synthesized via a solvothermal reaction.

Industrial Applicability

The present invention can provide a fine particle composite comprising fine particles of a sulfide or sulfide complex comprising at least one element selected from the group consisting of molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) and conductive fine particles. Such fine particle composite comprising fine particles of a sulfide or sulfide complex comprising a given element and conductive fine particles can be used for known applications. Further, development thereof can be expected in various applications by making use of its properties. For example, such substance can be used for a catalyst for a fuel cell that can be operated in a cost-effective manner. Furthermore, adequate selection of a dopant element with which the particle is to be doped can lead to manifestation of various physical properties.

What is claimed is:

1. A method for producing a fine particle composite comprising fine particles of a sulfide or sulfide complex comprising at least one element selected from the group consisting of molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re) and conductive fine particles comprising steps of:

preparing a solvent mixture from a compound containing conductive carbon powder, at least one compound containing an element selected from among molybdenum (Mo), rhodium (Rh), ruthenium (Ru), and rhenium (Re), and sulfur (S); and

conducting a hydrothermal or solvothermal reaction at a pressure and temperature that convert the solvent mixture into a supercritical or subcritical water or solvent.

2. The method for producing a fine particle composite according to claim 1, wherein the step of hydrothermal or solvothermal reaction is carried out at 200°C to 600°C.

3. The method for producing a fine particle composite according to claim 1 or 2, wherein the step of hydrothermal or solvothermal reaction is followed by thermal treatment in an inert gas atmosphere at 300°C to 800°C.

4. The method for producing a fine particle composite according to any of claims 1 to 3, wherein the conductive carbon powder is carbon black and/or carbon nanotubes.

5. The method for producing a fine particle composite according to any of claims 1 to 4, wherein the reaction is carried out *in situ*.

Application number/numéro de demande: JP2008/066937

Figures: 3, 5, 9, 10, 12, 15, 17, 19, 22, 26, 27, 31, 35, 37,
38, 39, 45, 46, 49, 50, 54, 60

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Fig. 1

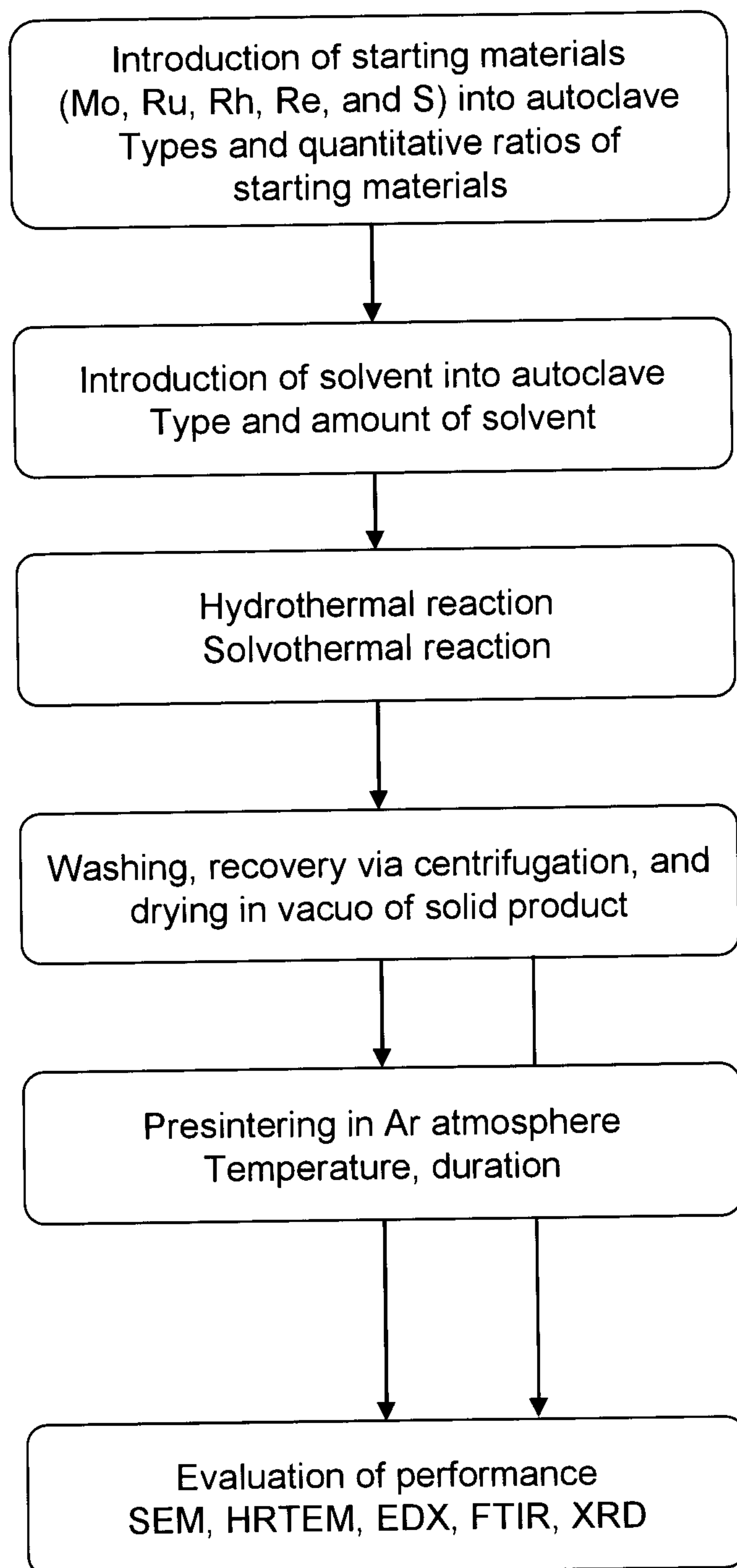


Fig. 2

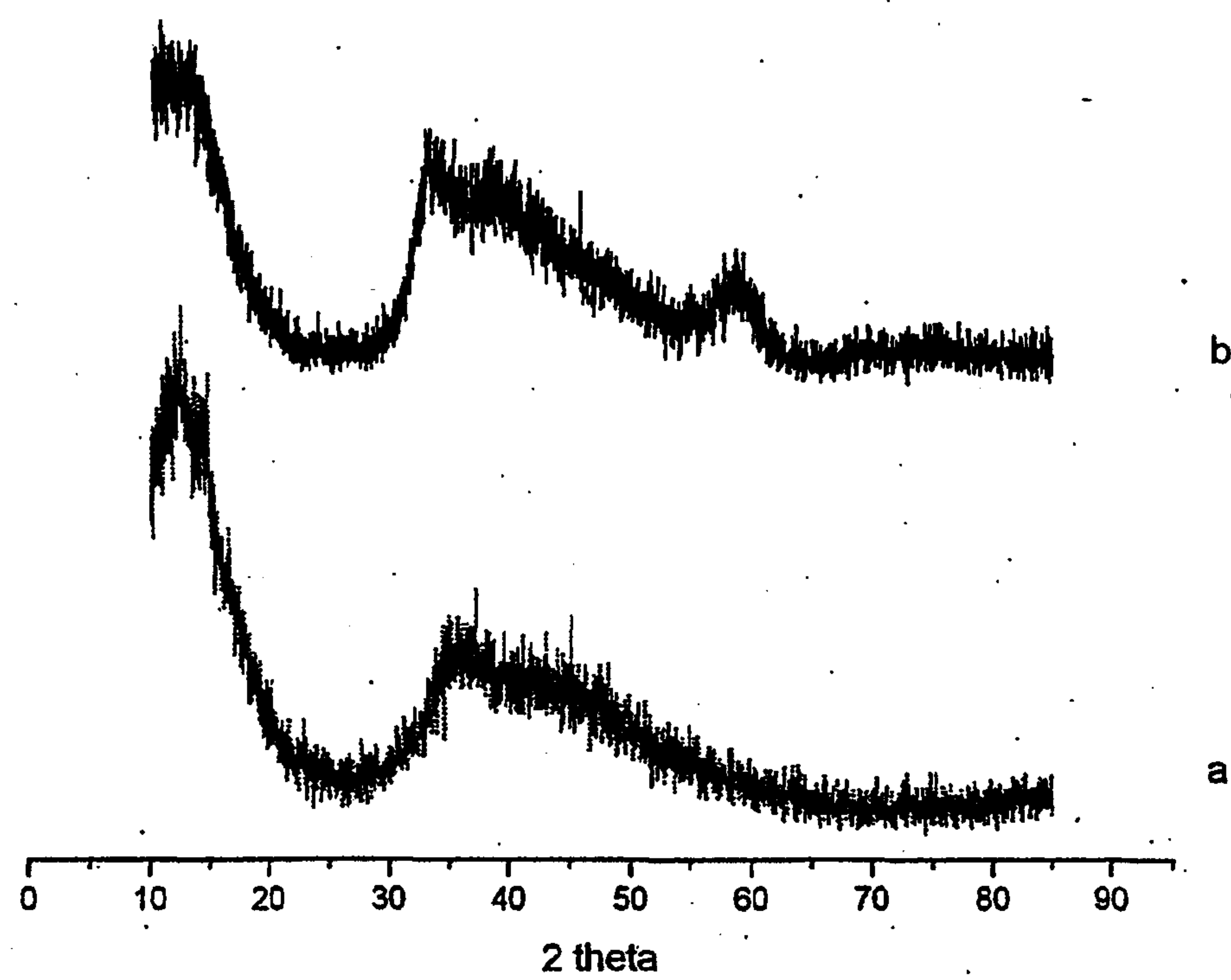


Fig. 4

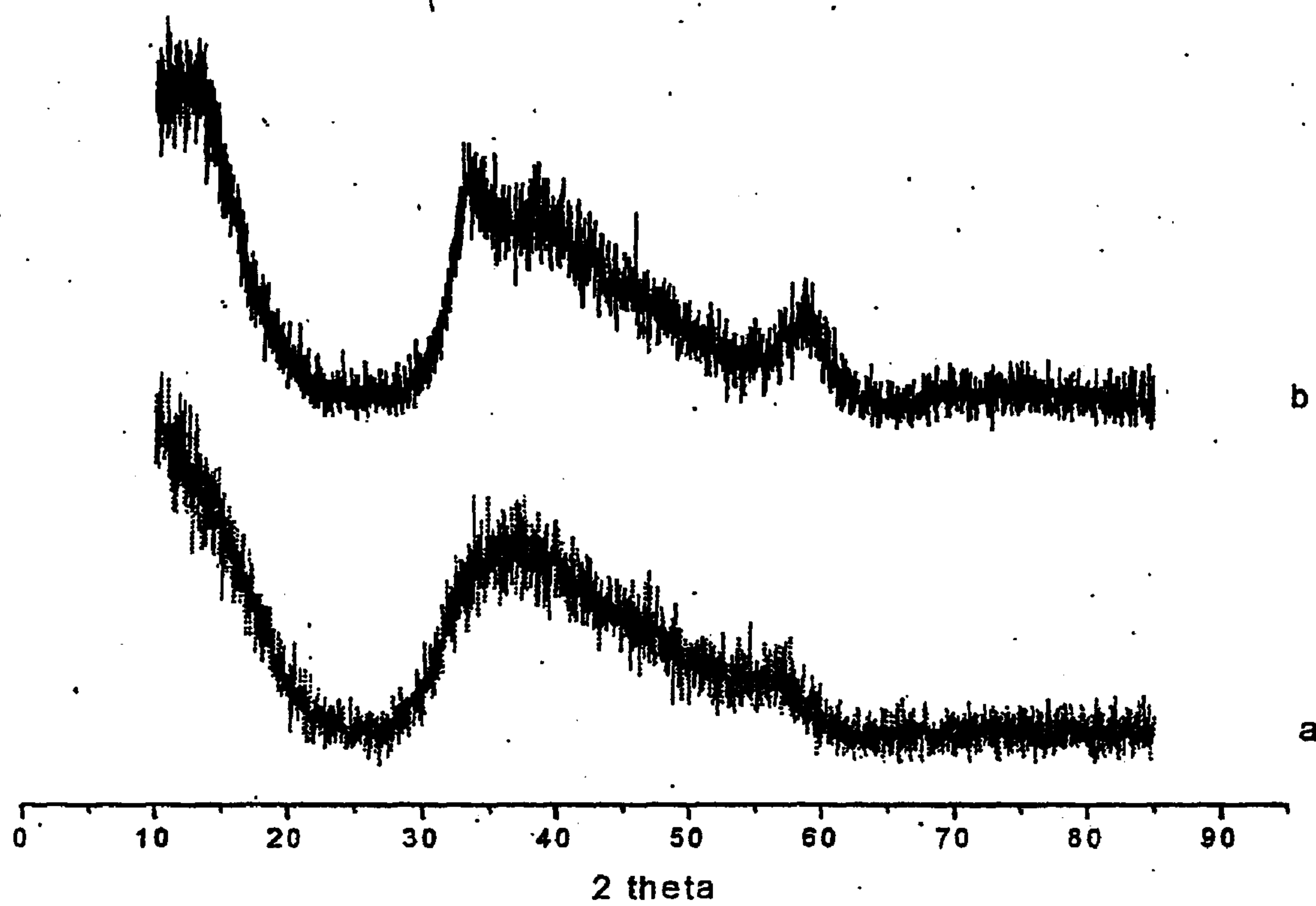


Fig. 6

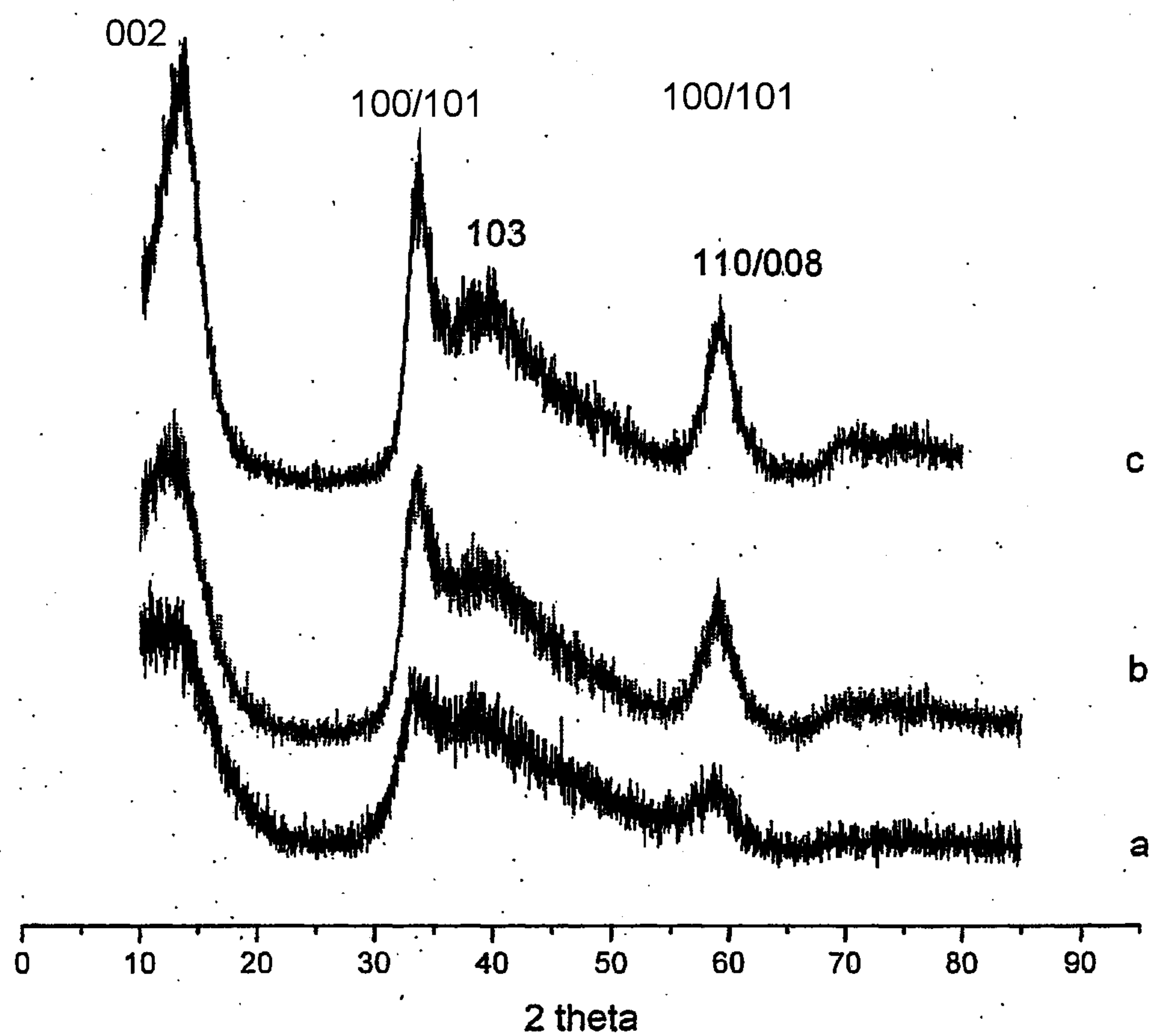


Fig. 7

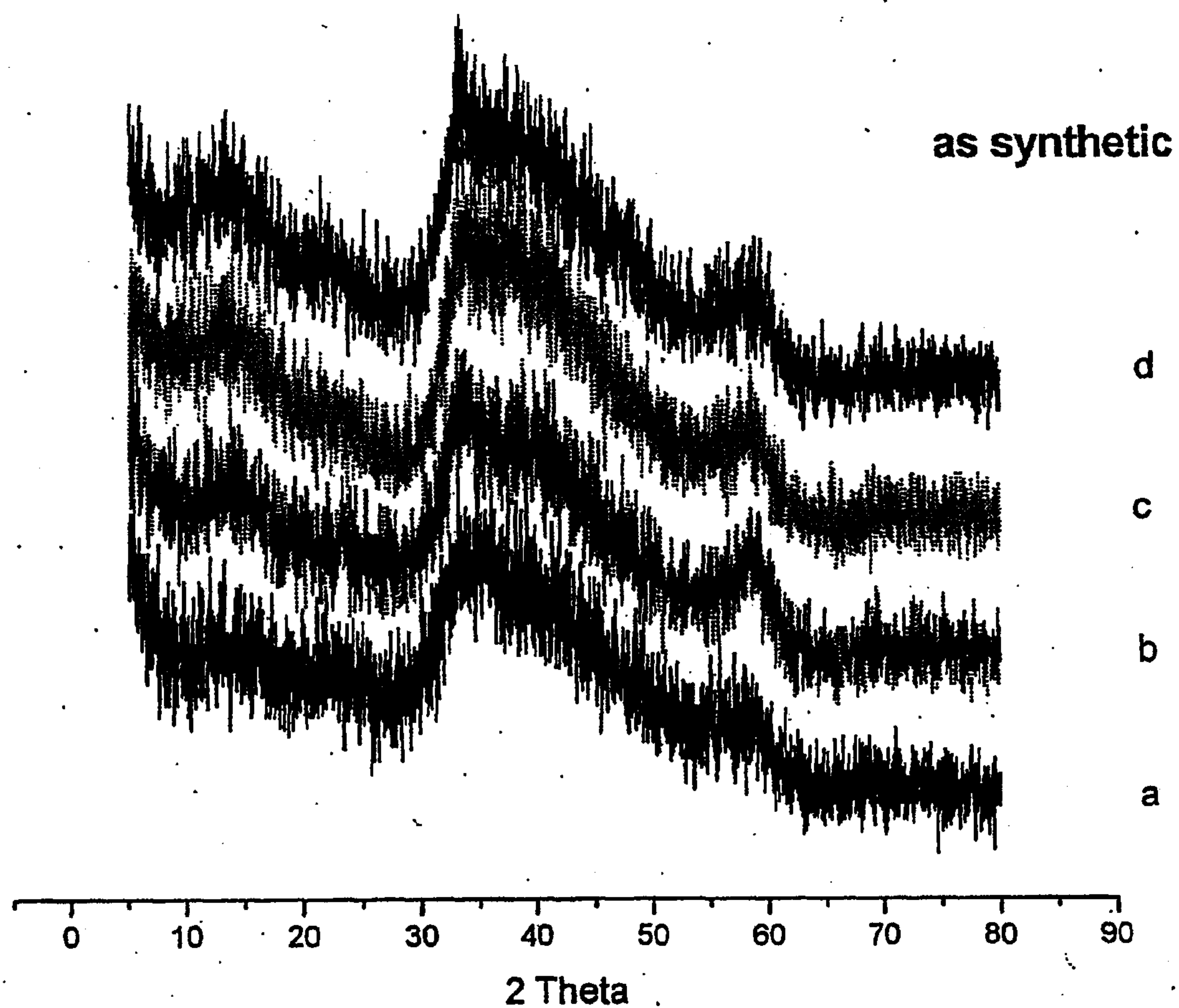


Fig. 8

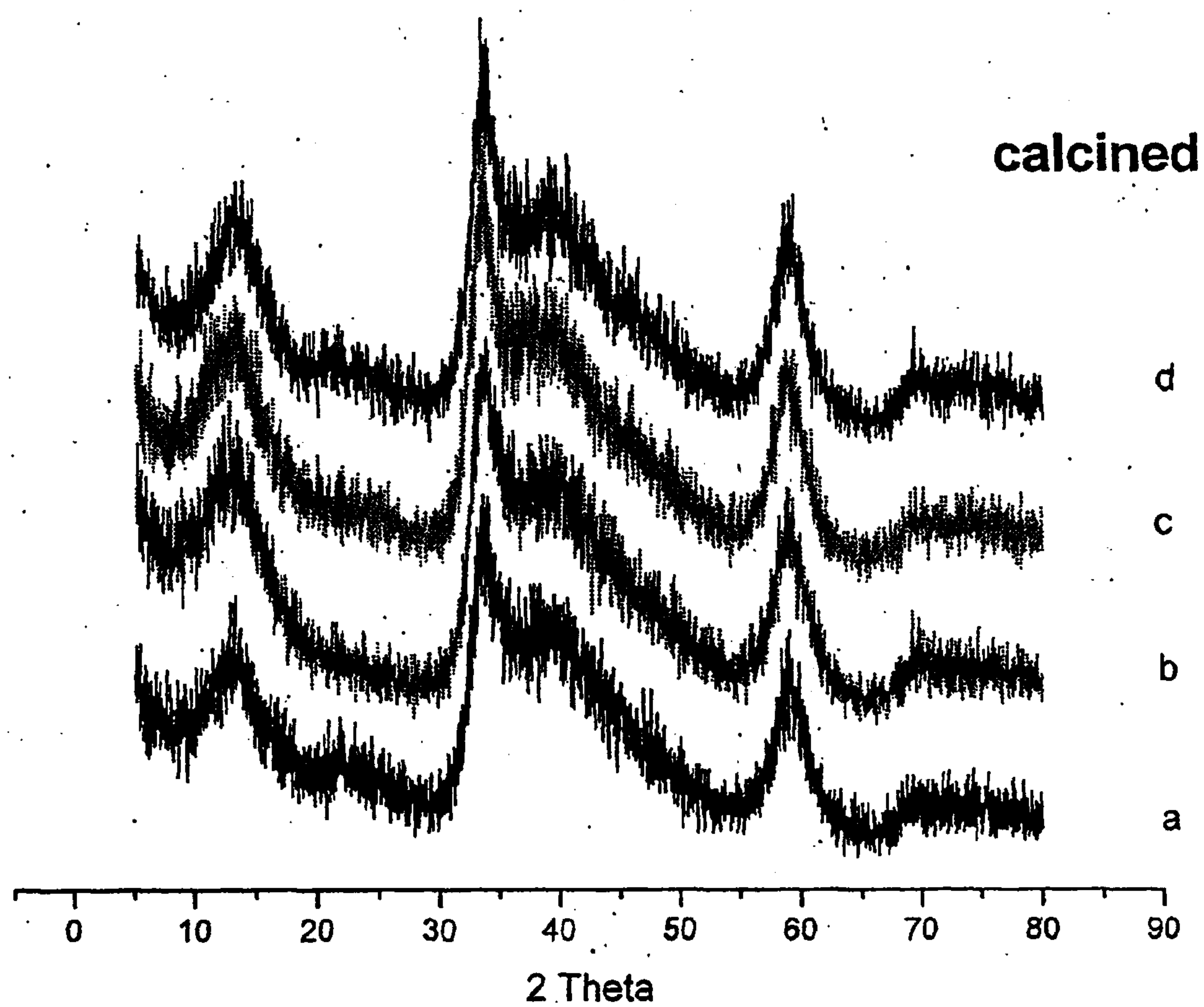


Fig. 11

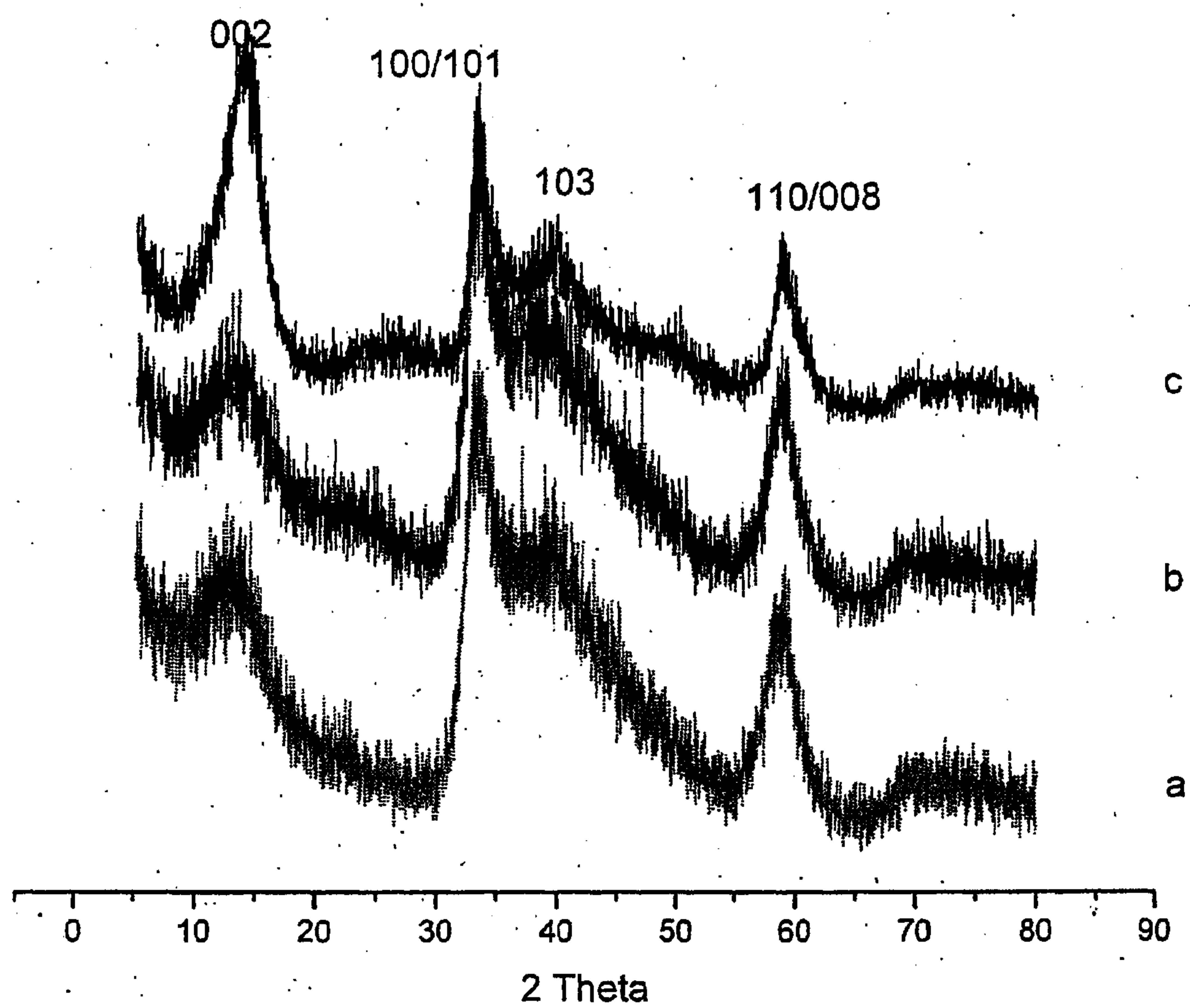


Fig. 13

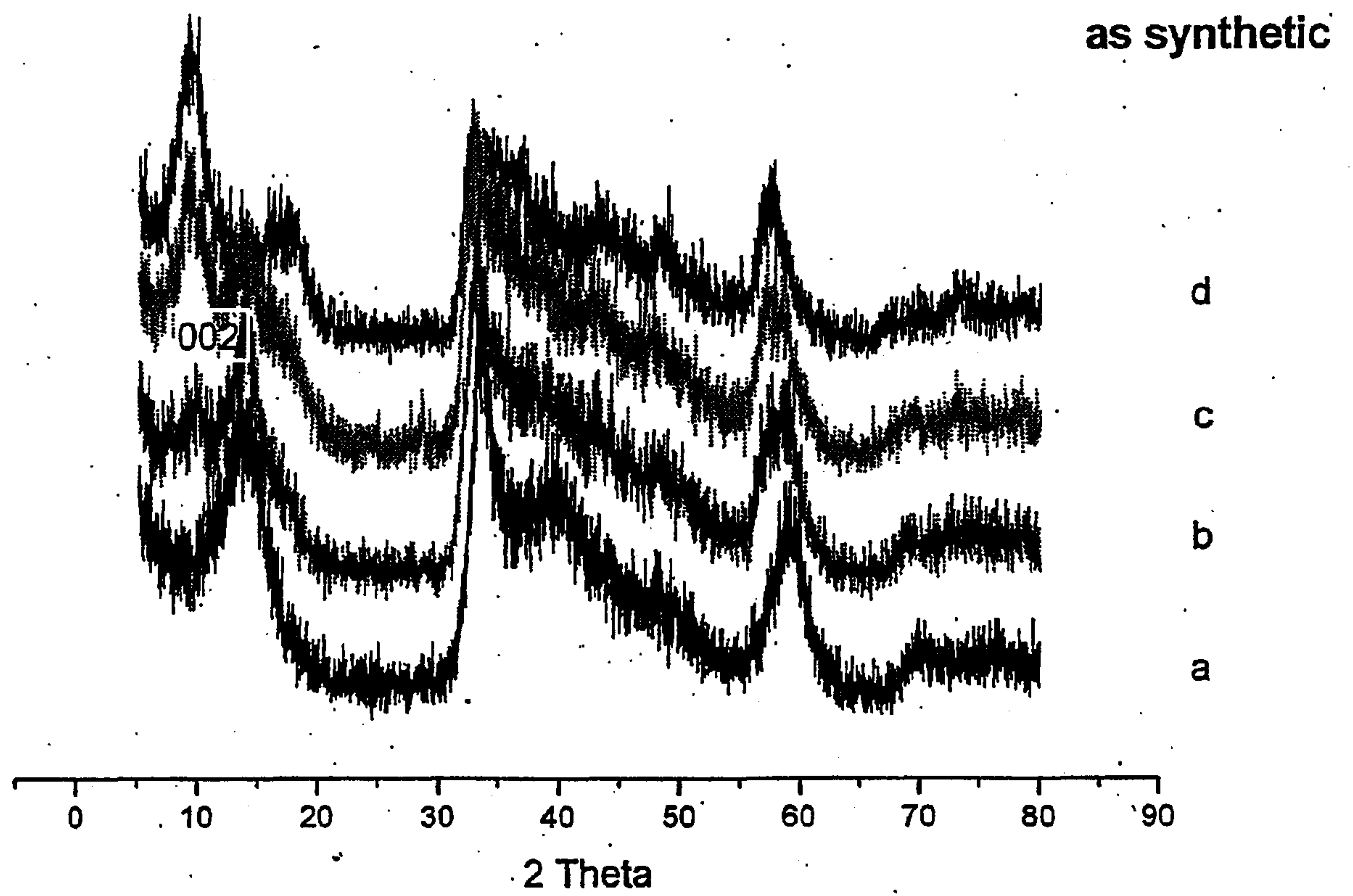


Fig. 14

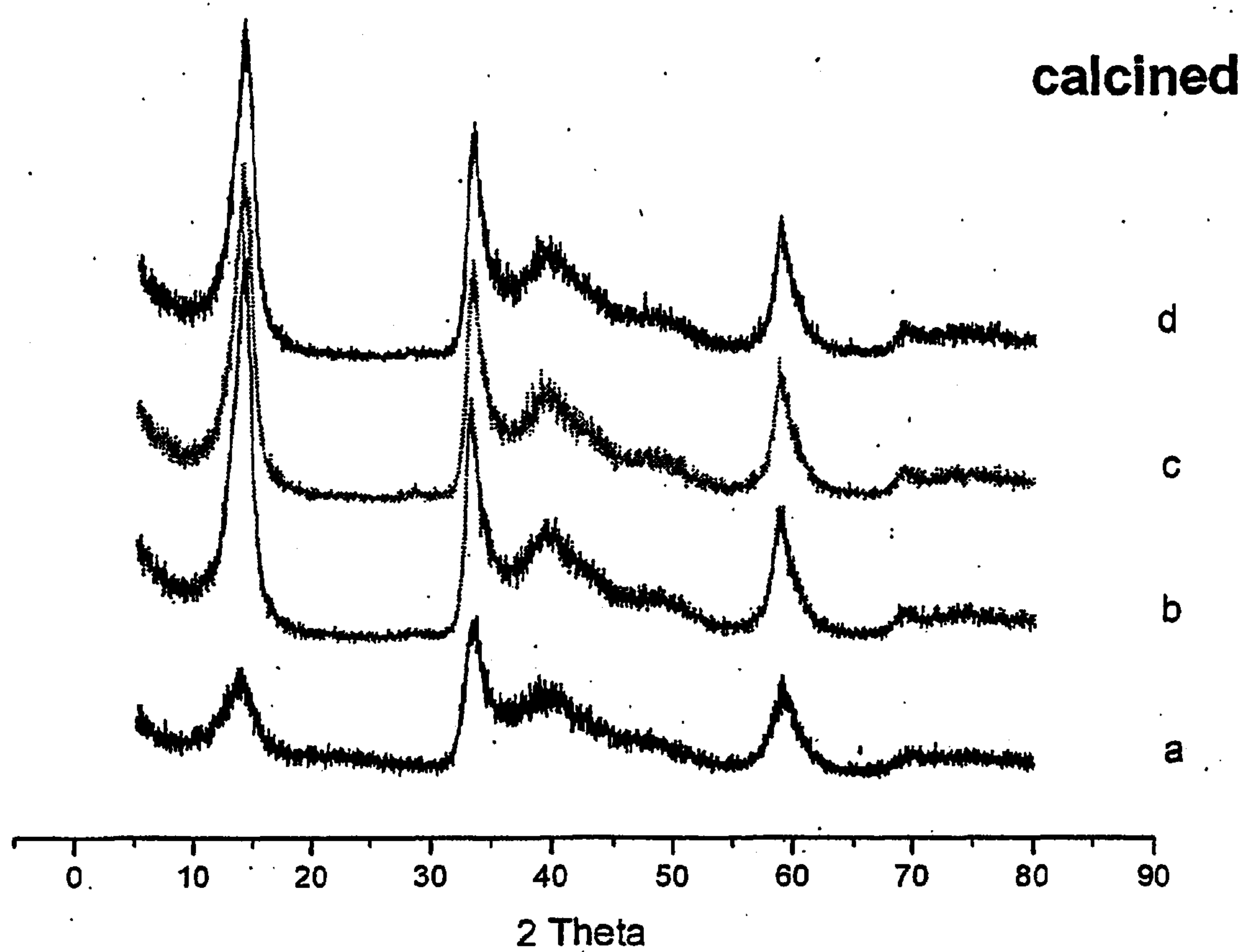


Fig. 16

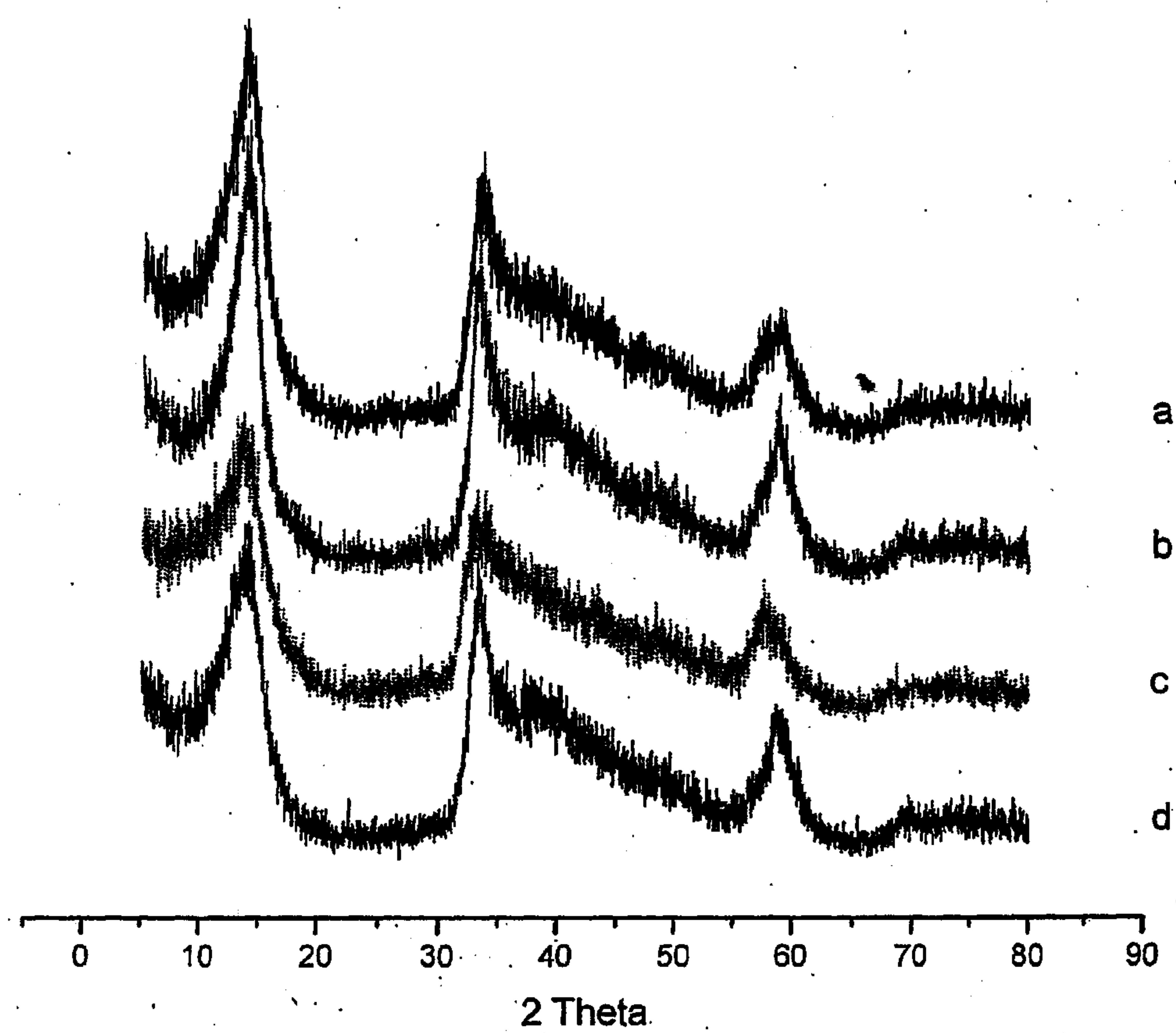


Fig. 18

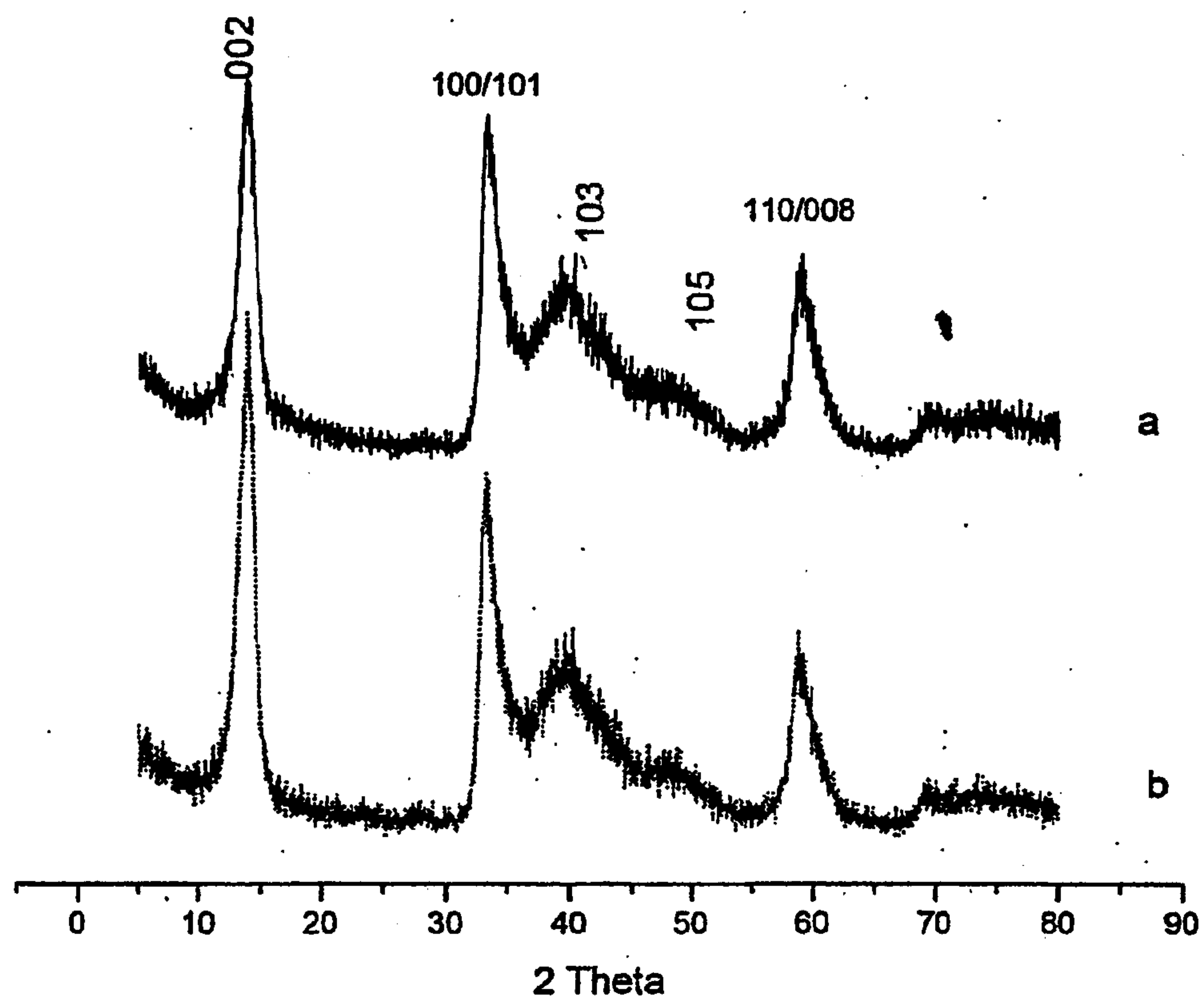


Fig. 20

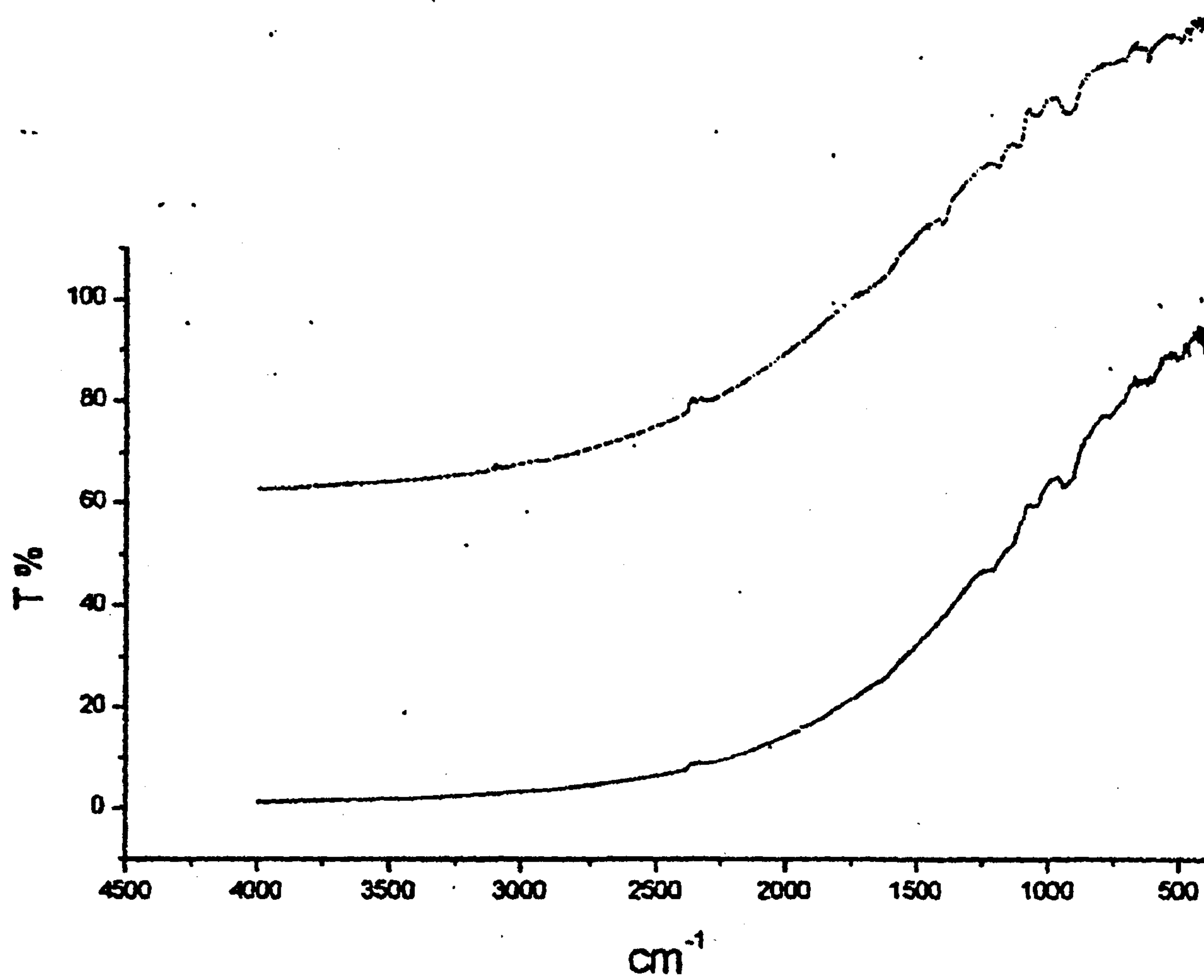


Fig. 21

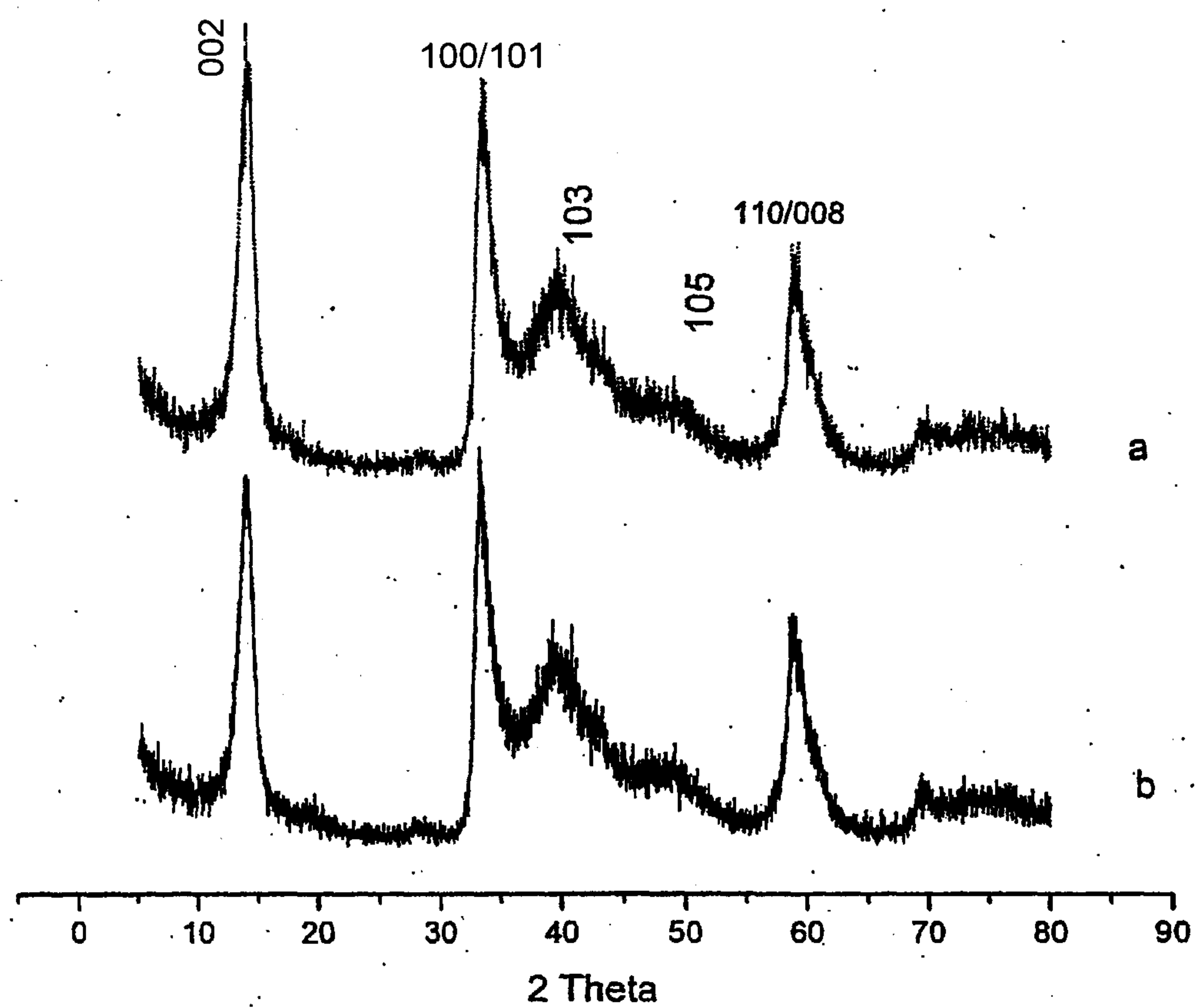


Fig. 23

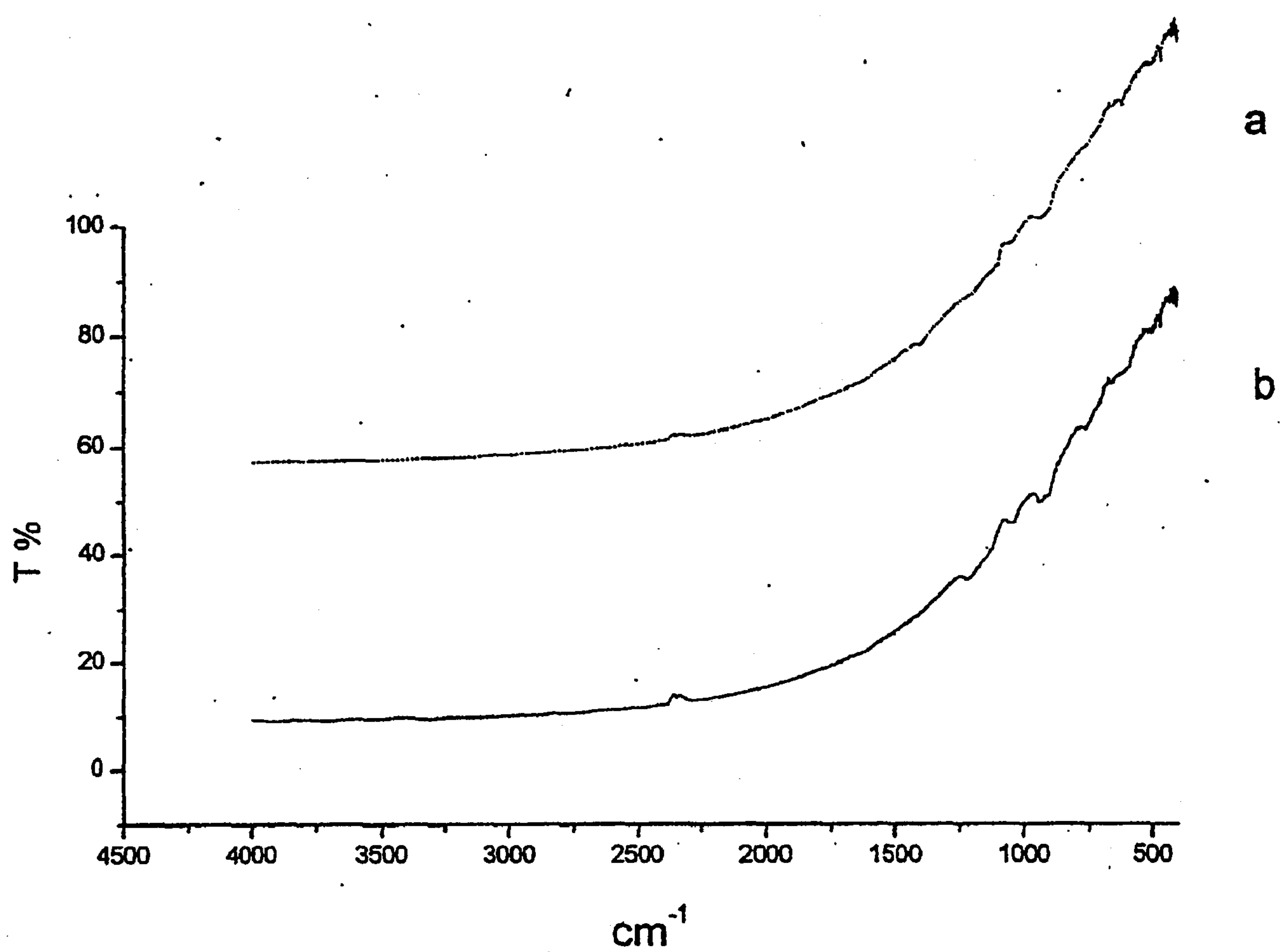


Fig. 24

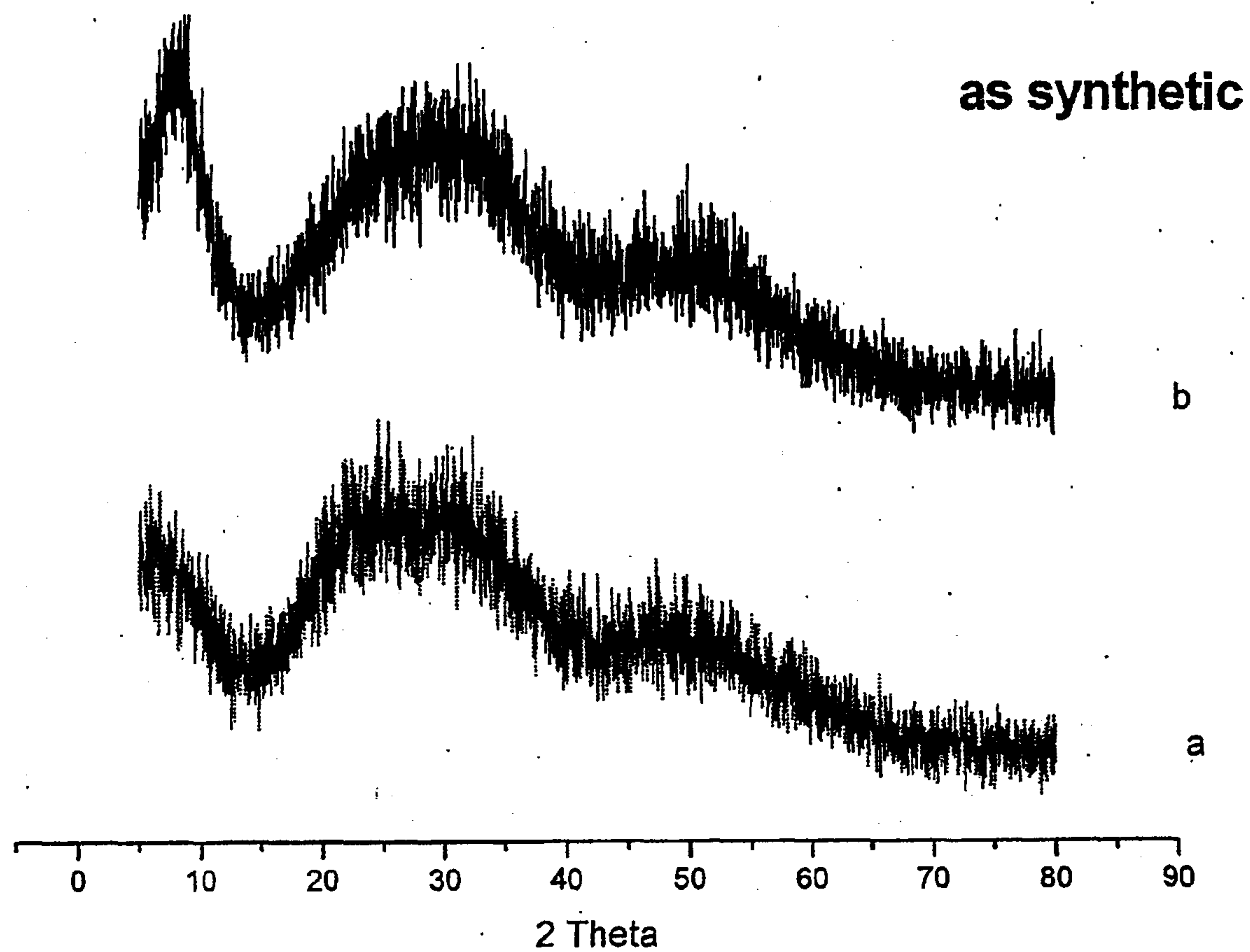


Fig. 25

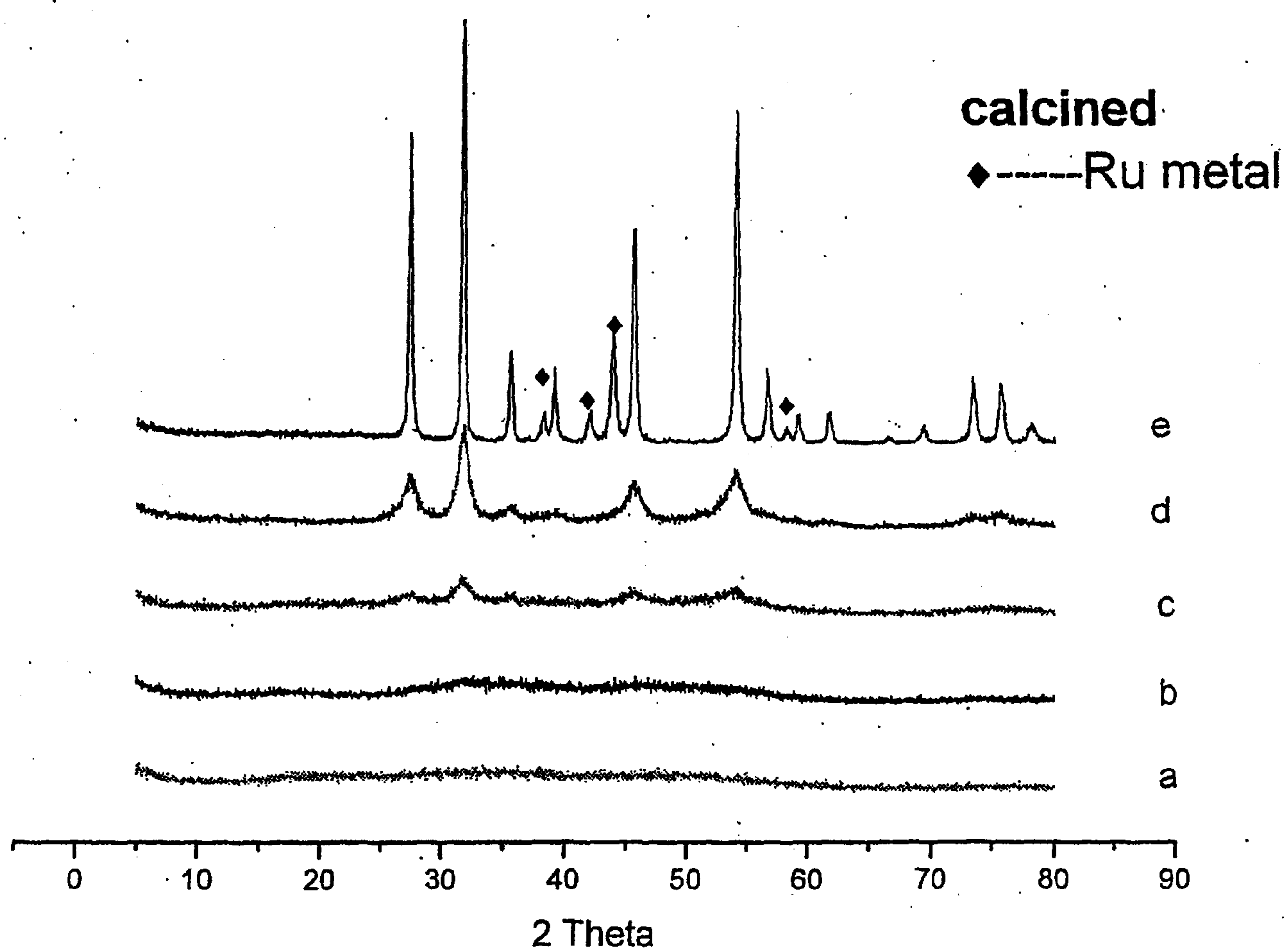


Fig. 28

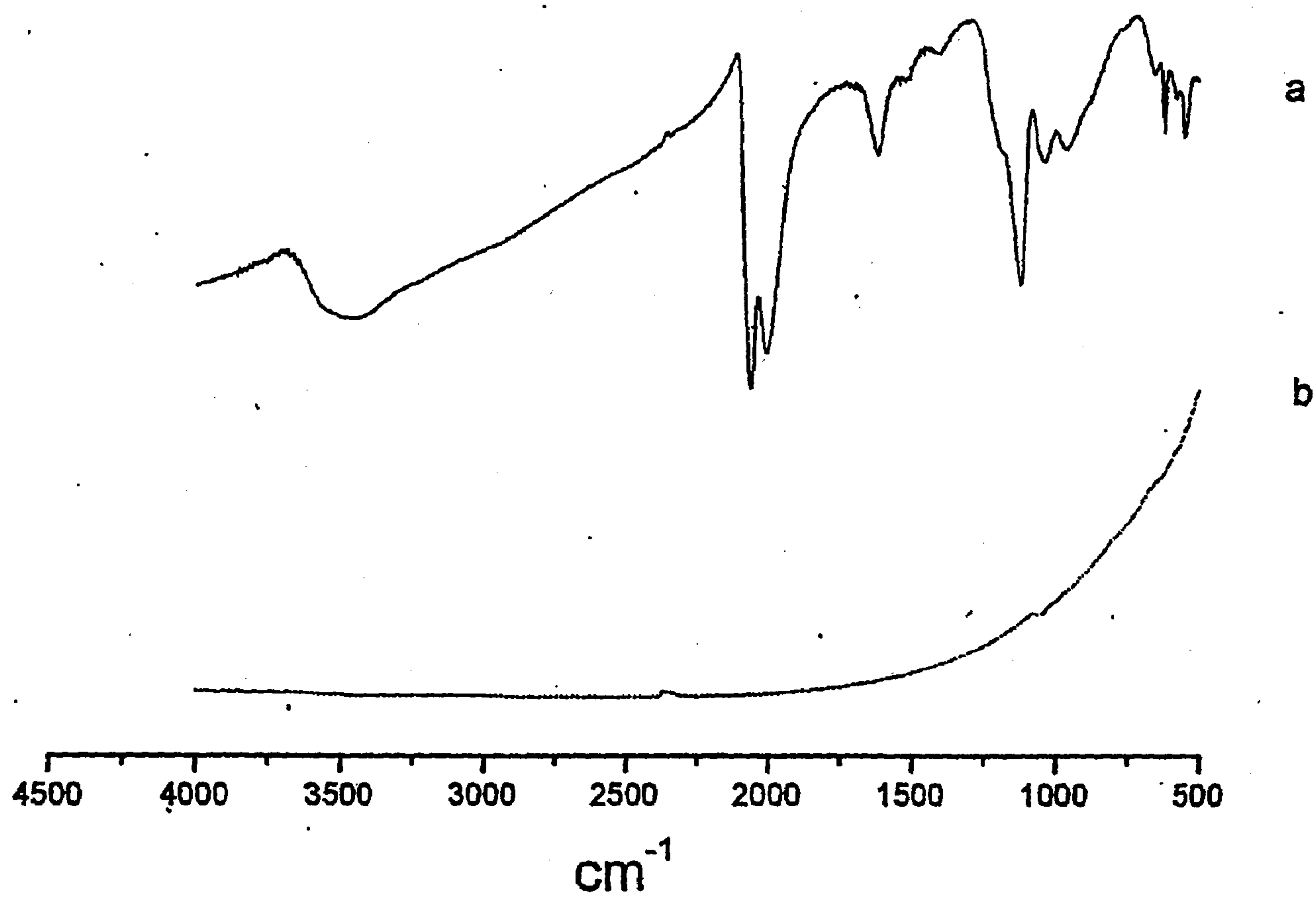


Fig. 29

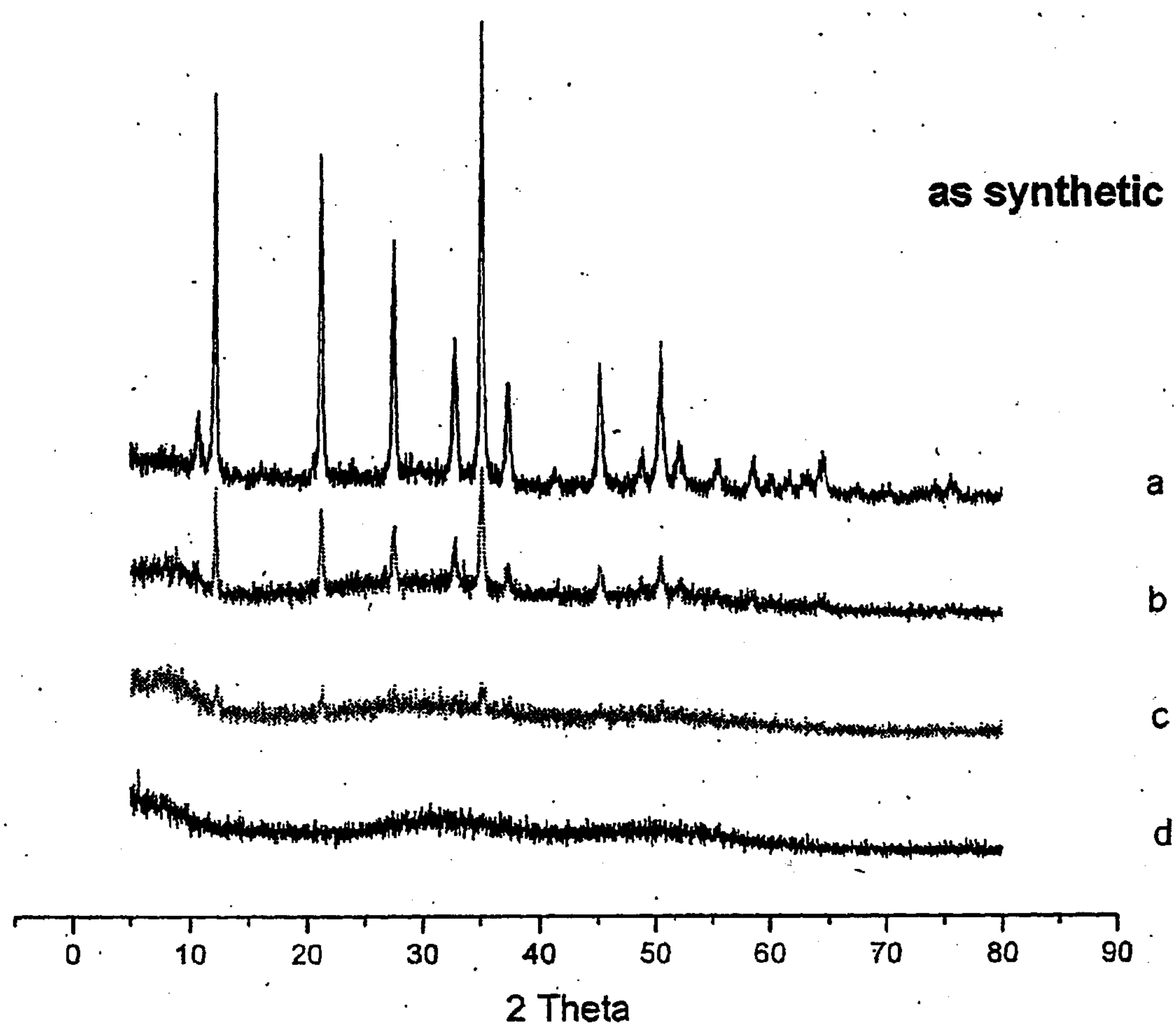


Fig. 30

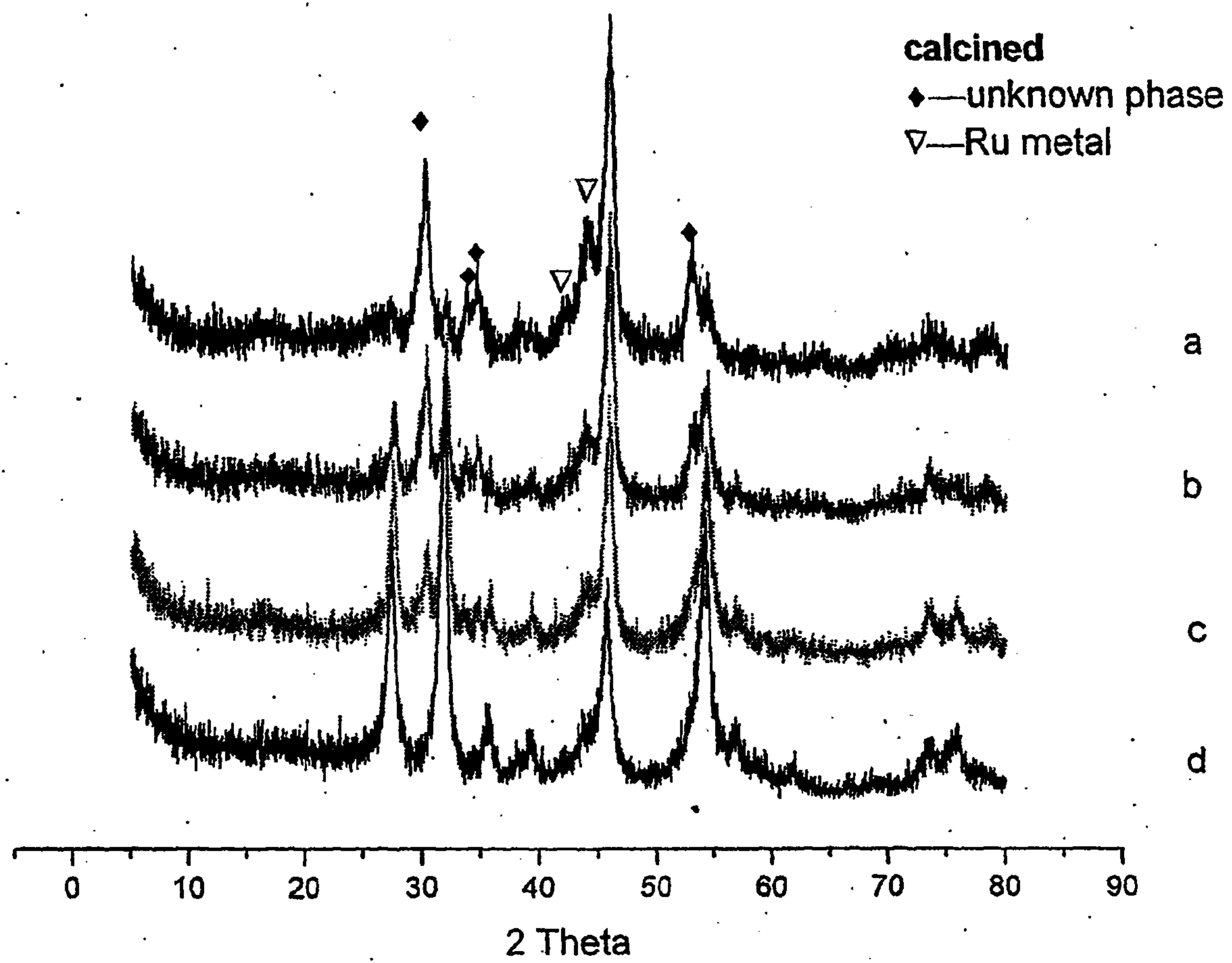


Fig. 32

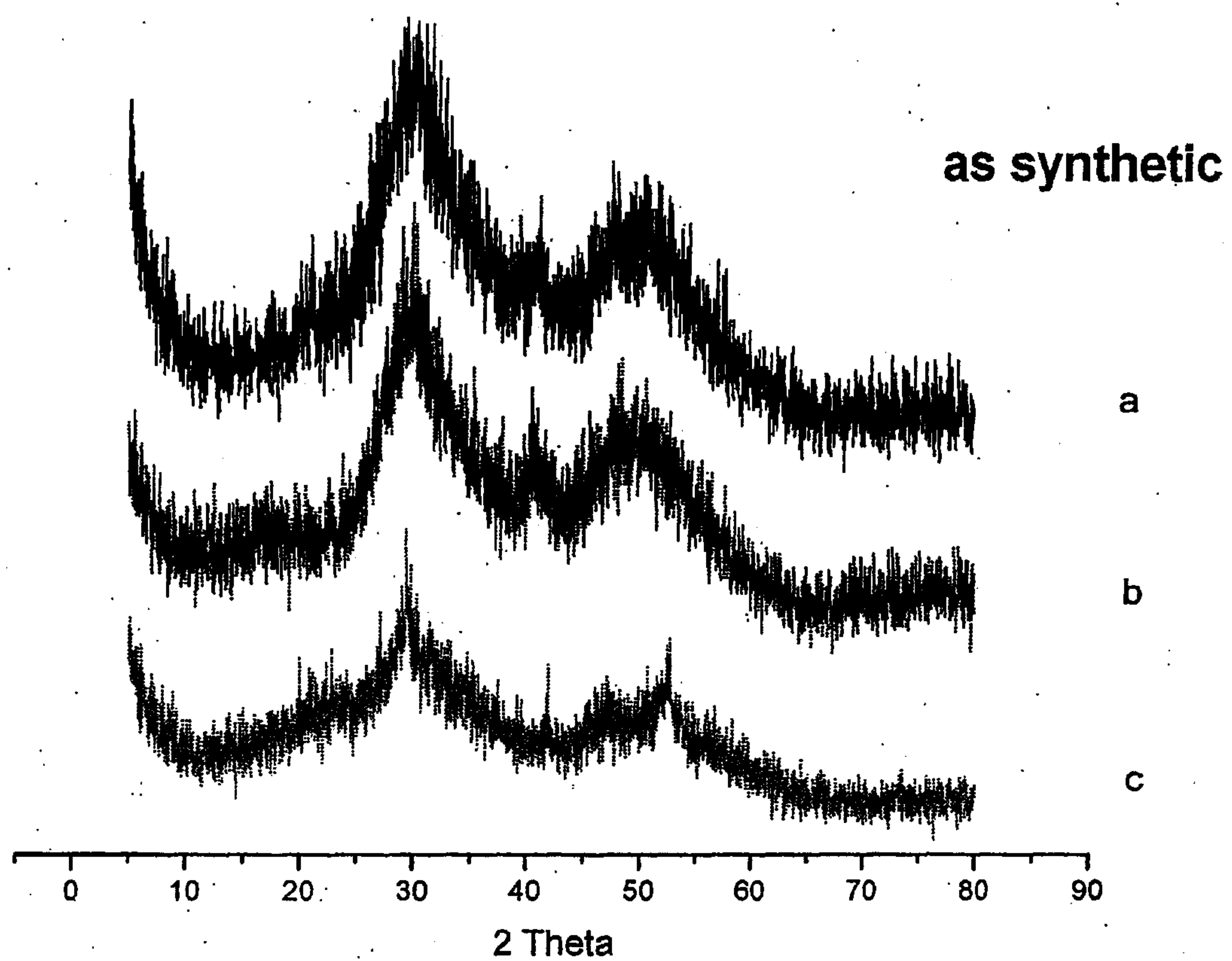


Fig. 33

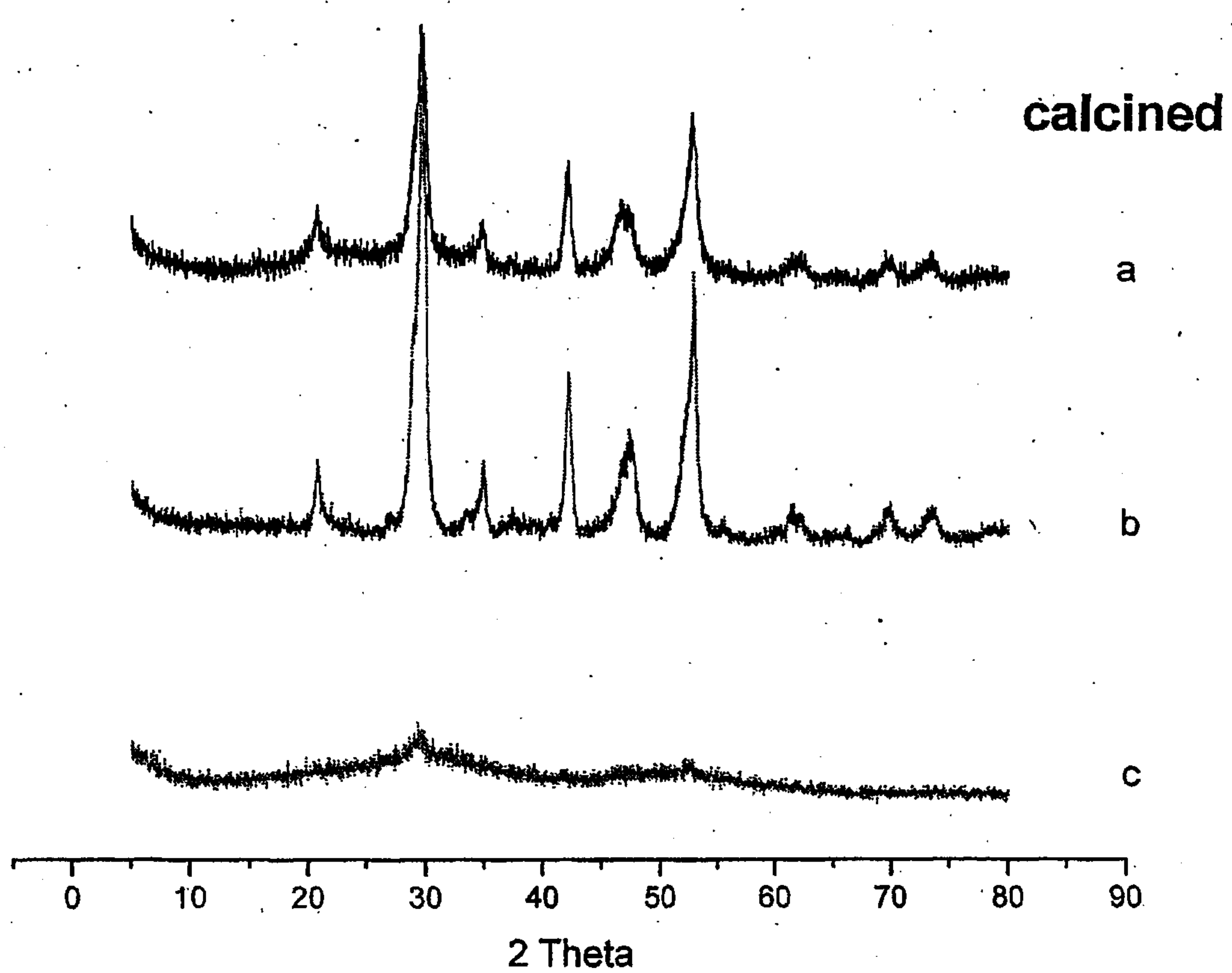


Fig. 34

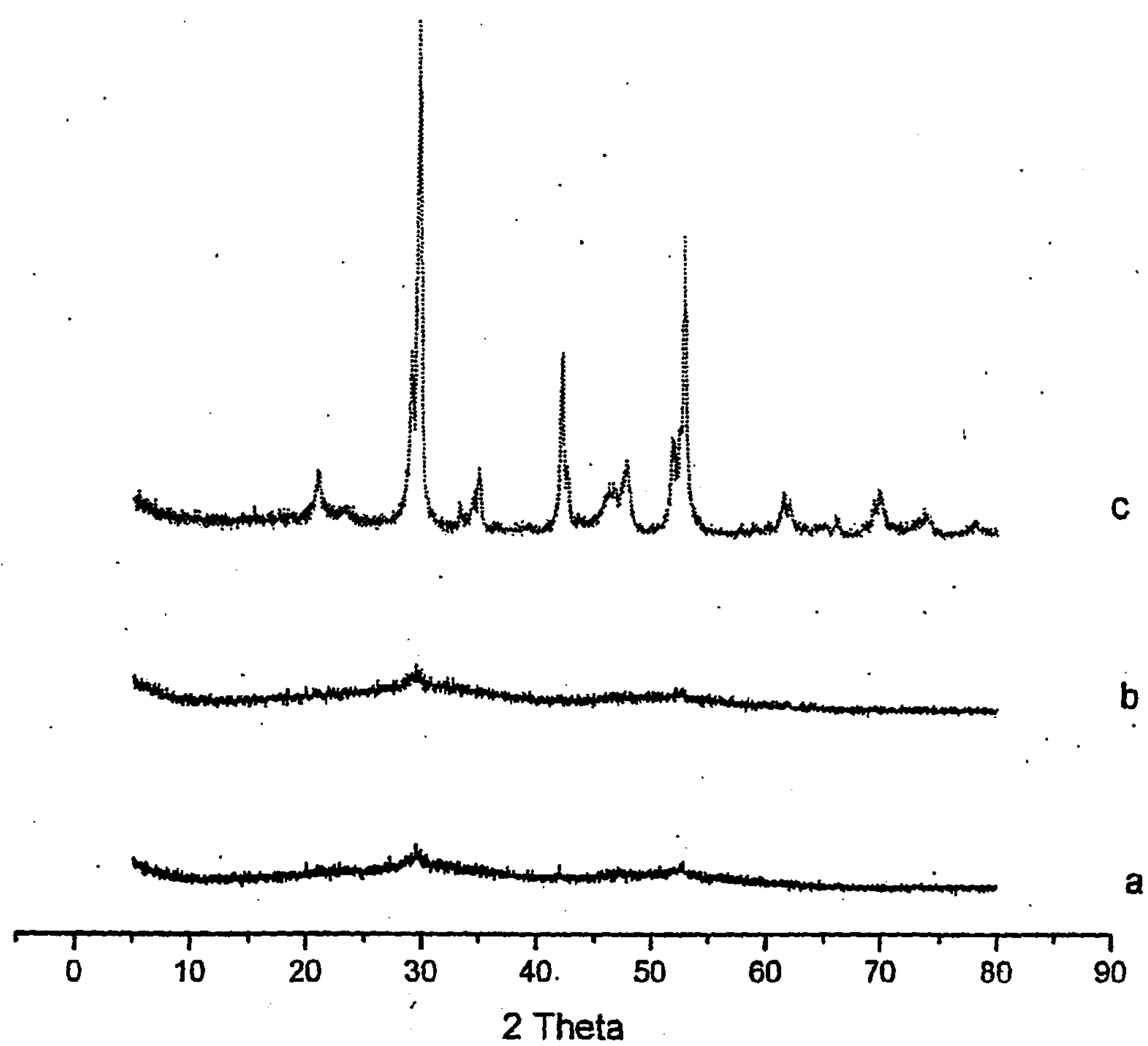


Fig. 36

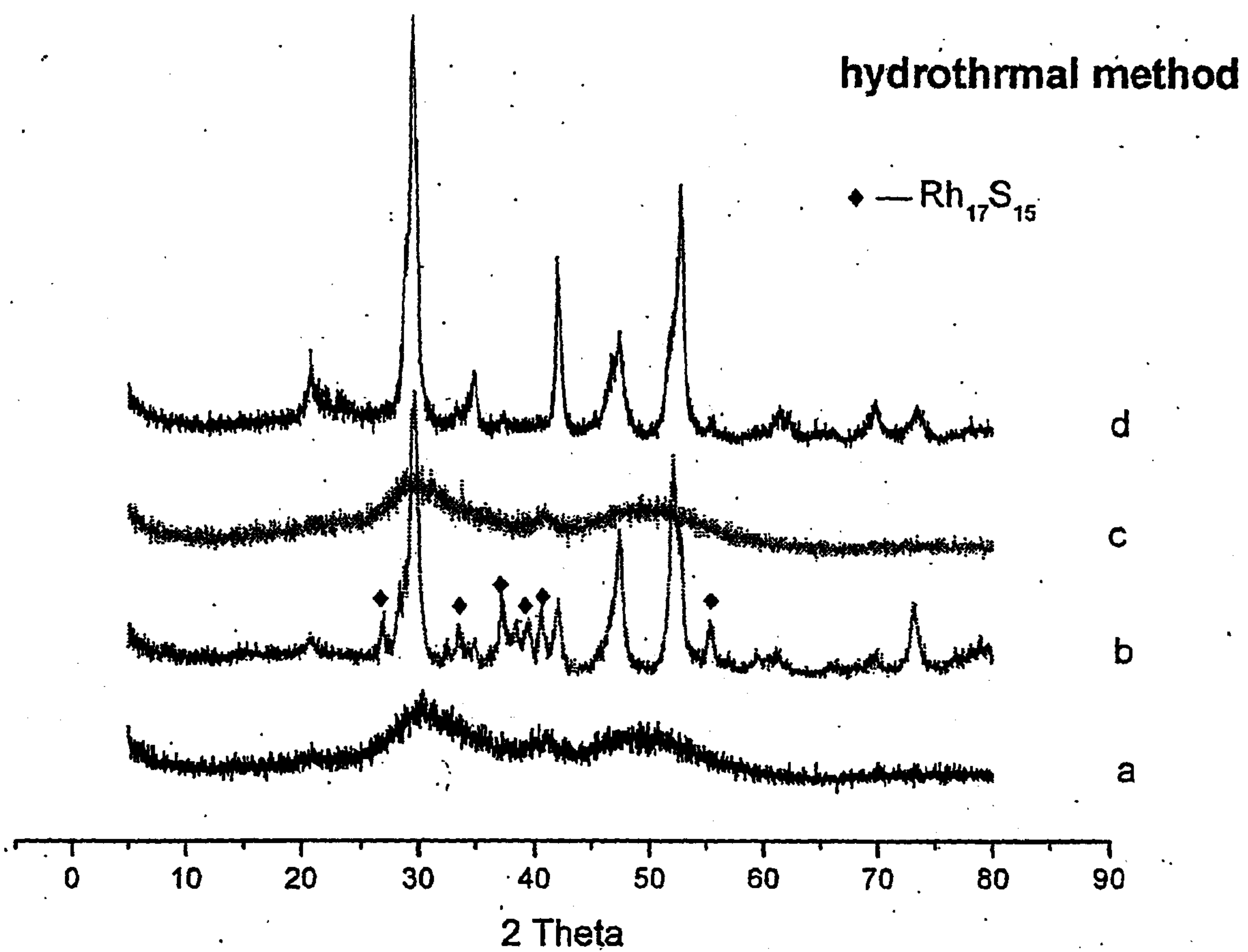


Fig. 40

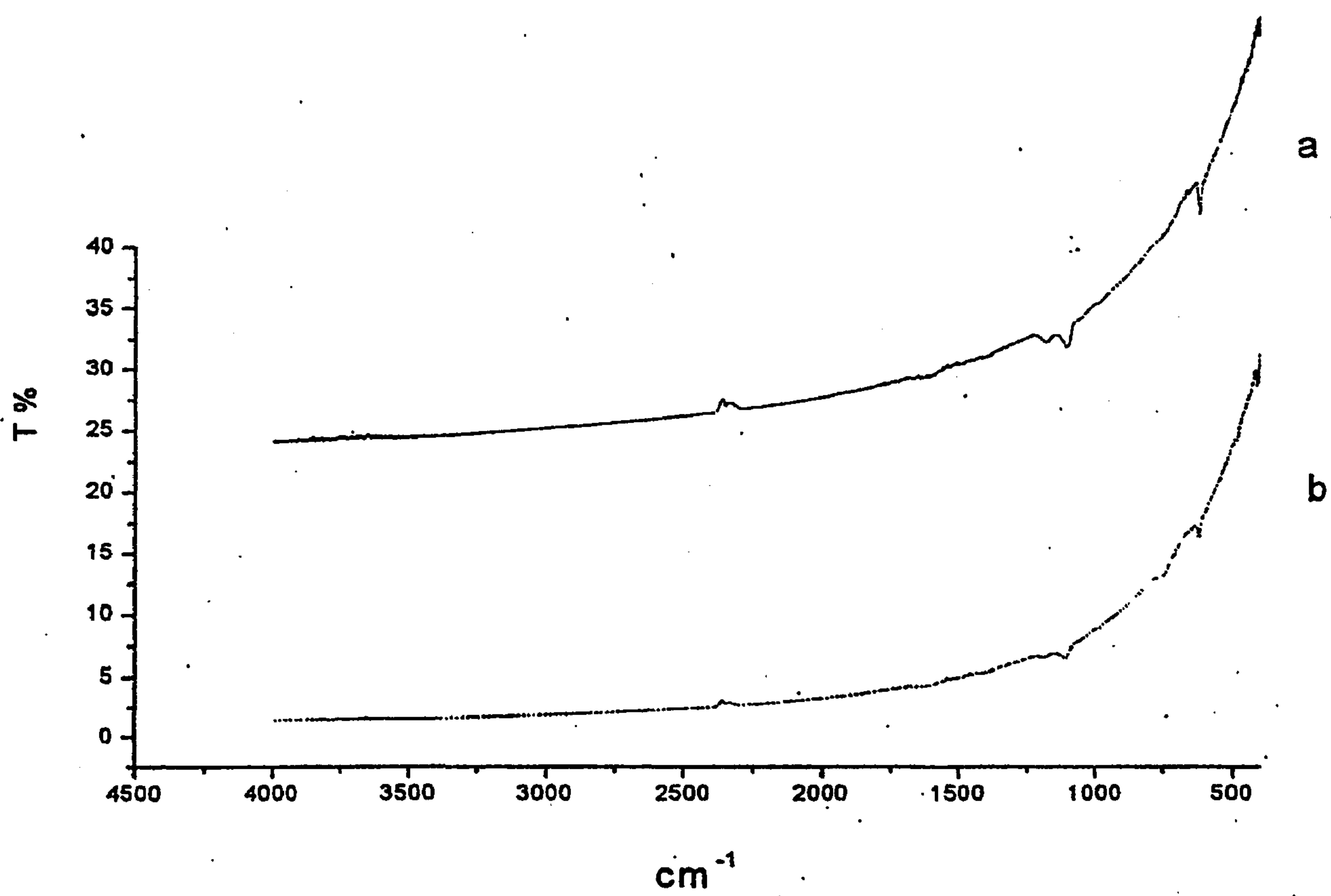


Fig. 41

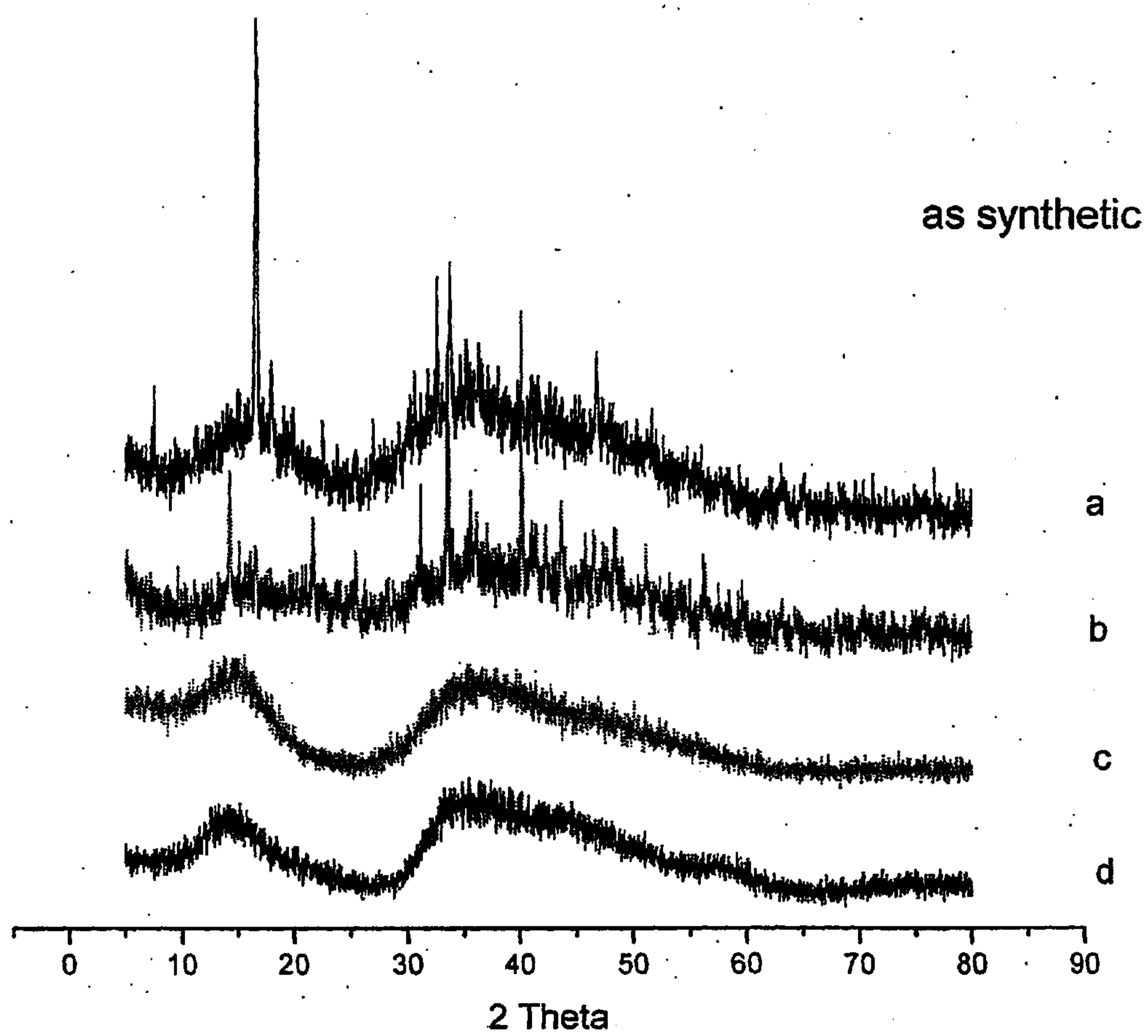


Fig. 42

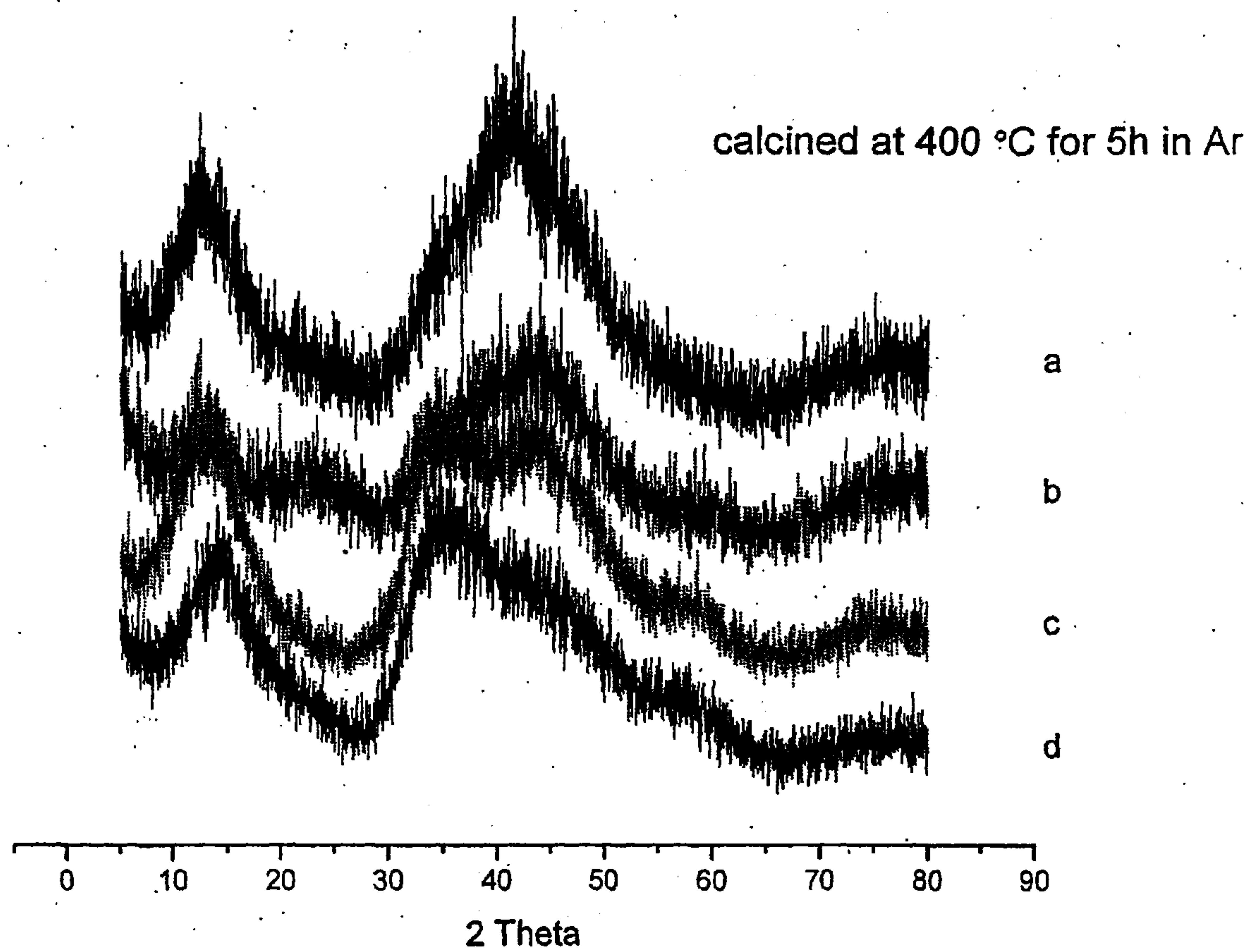


Fig. 43

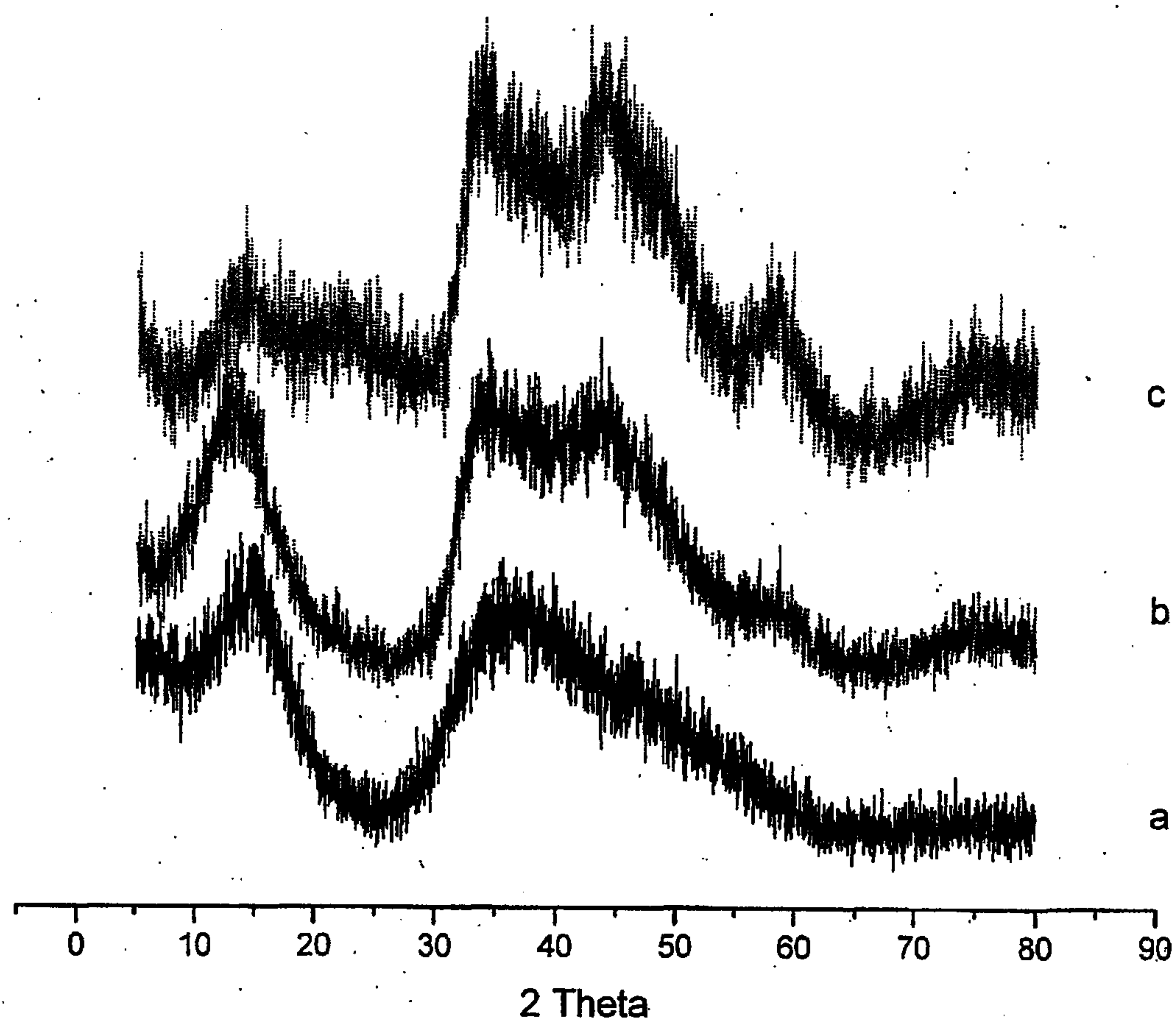


Fig. 44

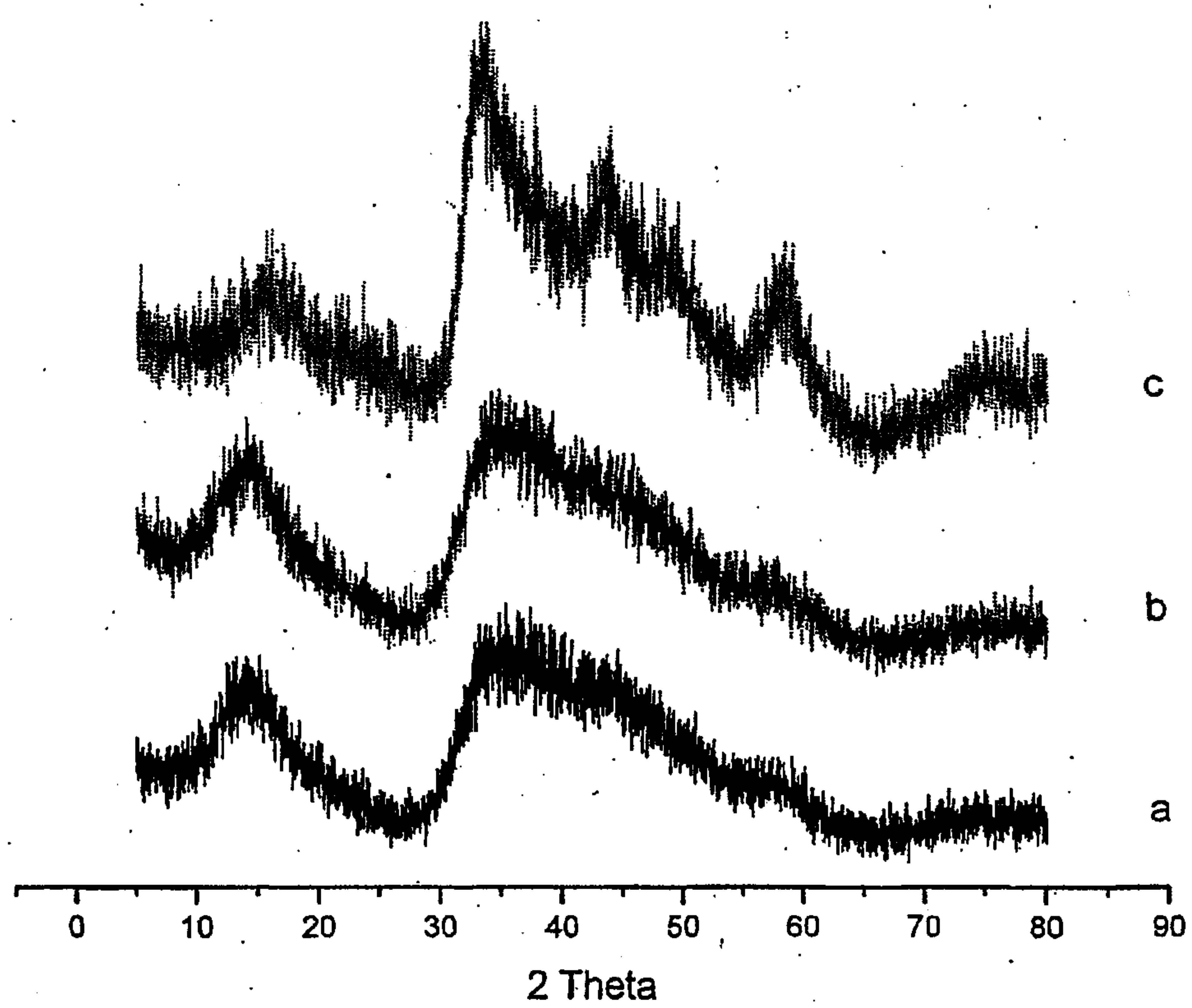


Fig. 47

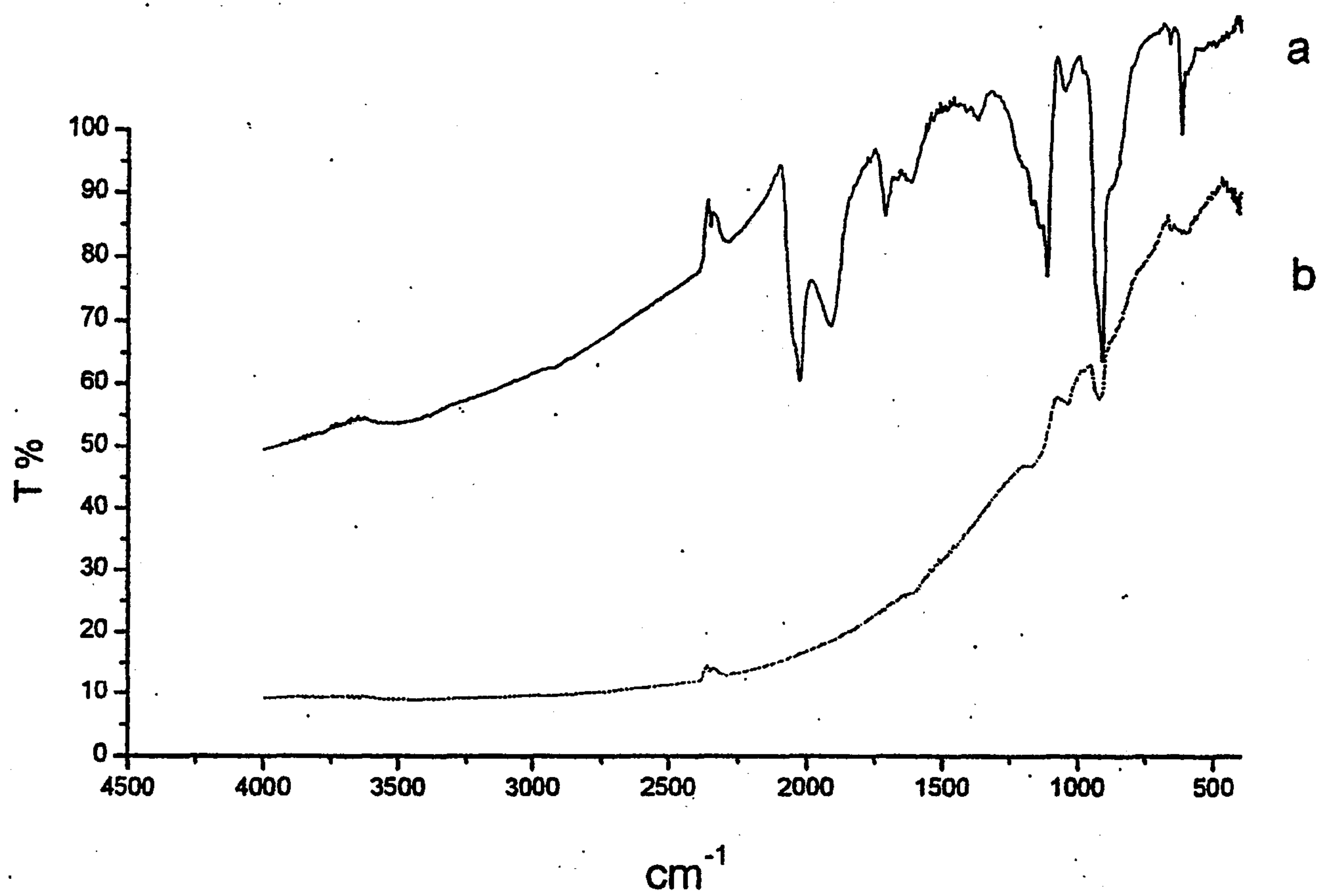


Fig. 48

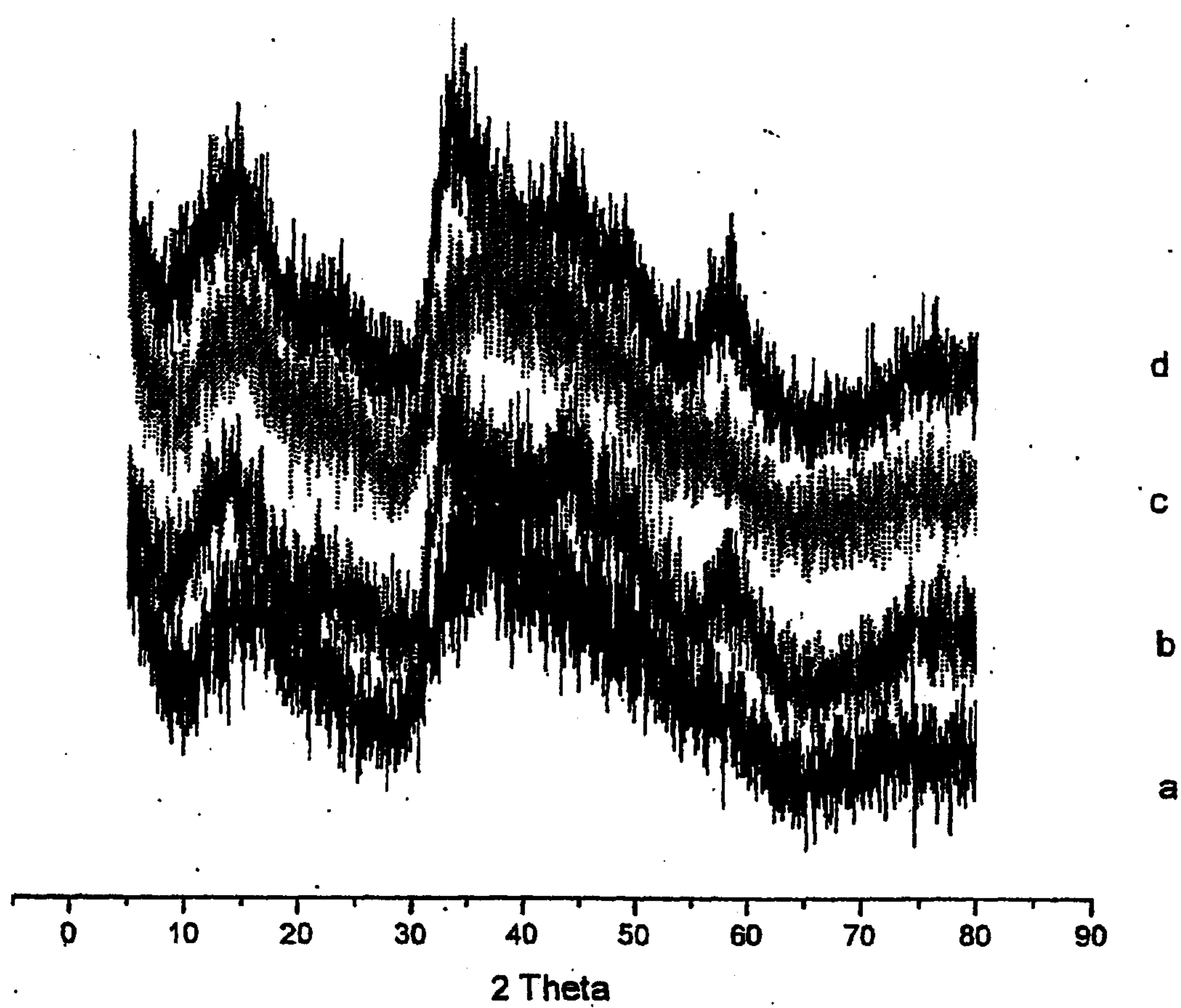


Fig. 51

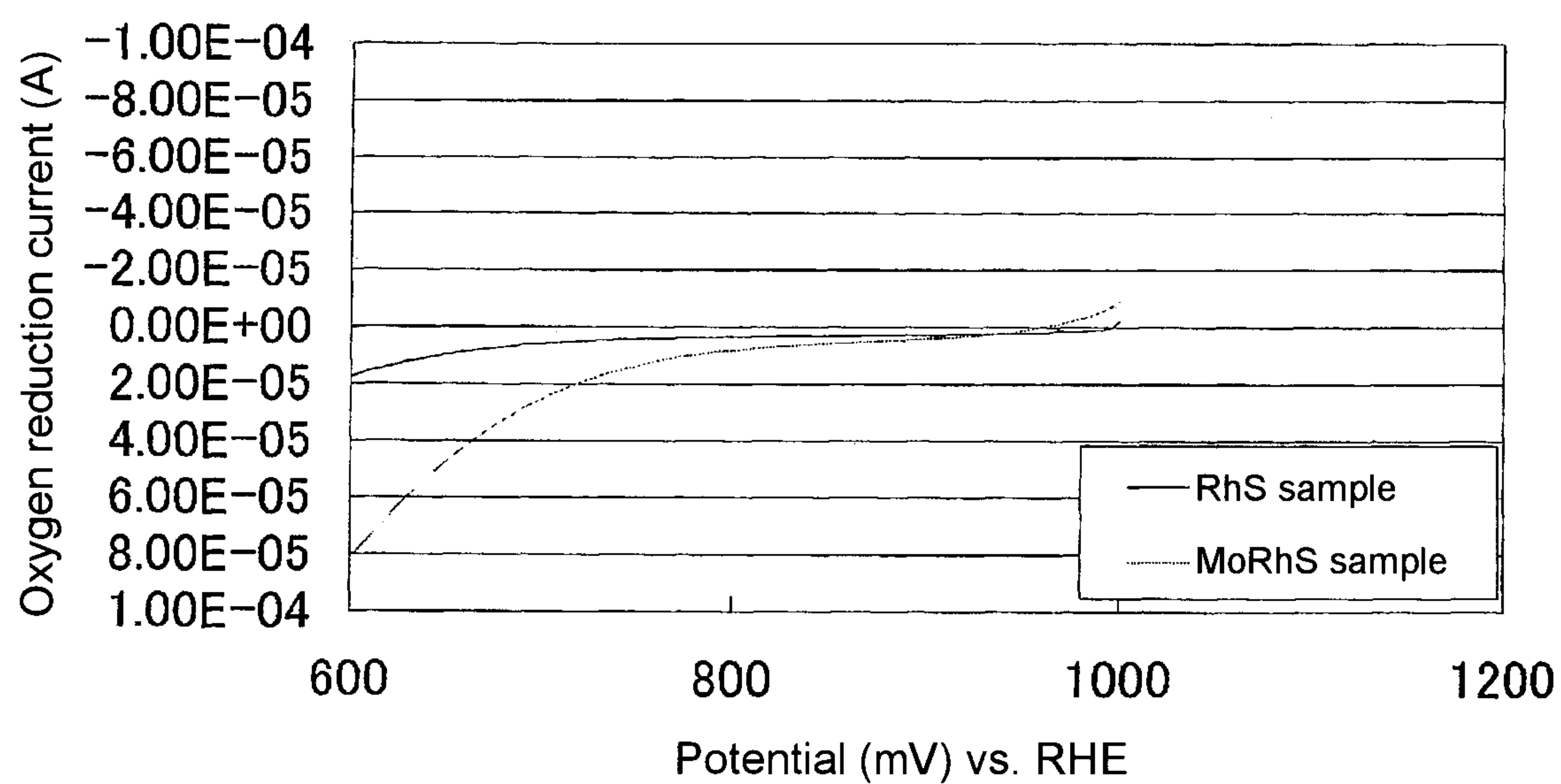


Fig. 52

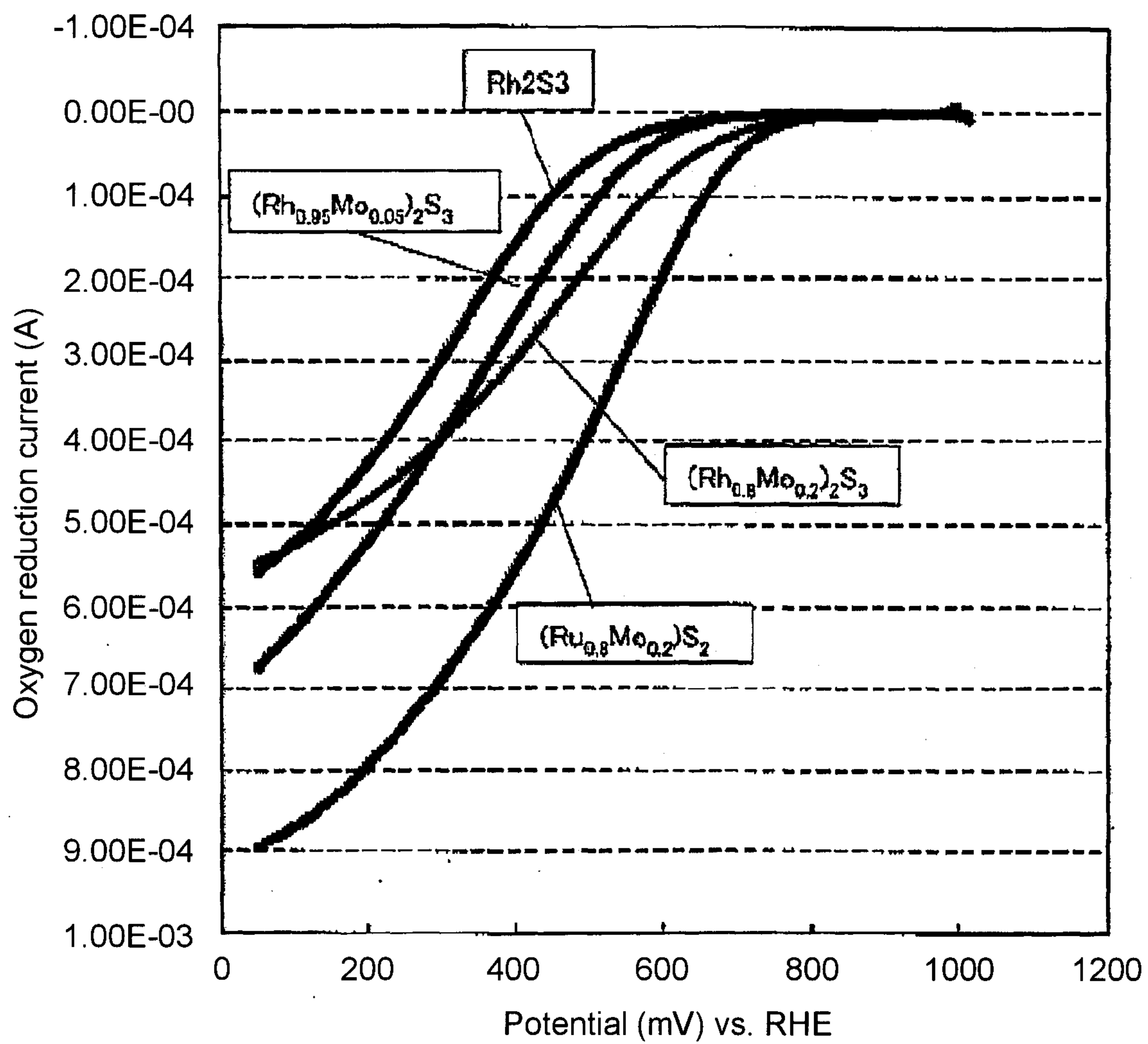


Fig. 53

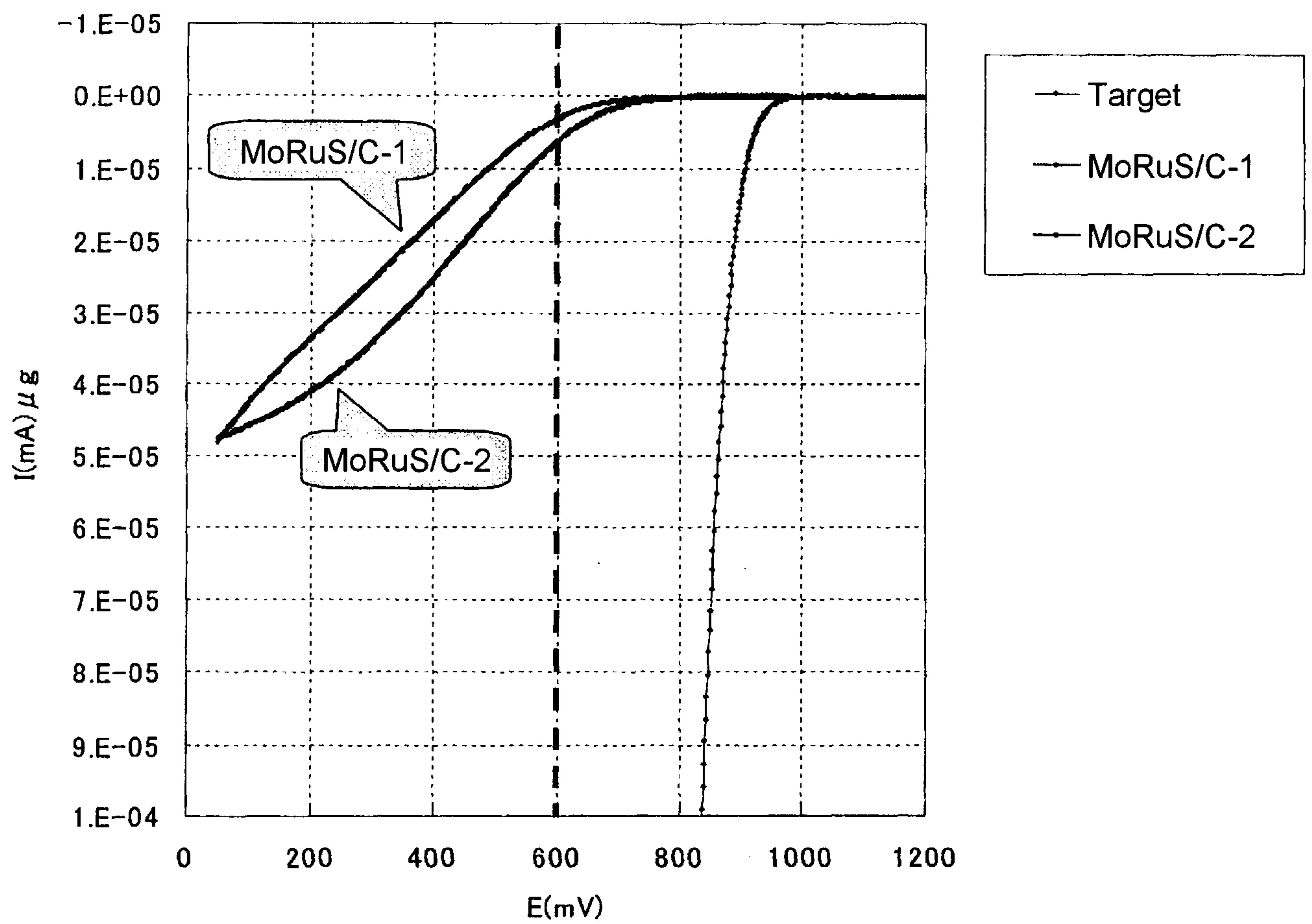


Fig. 55

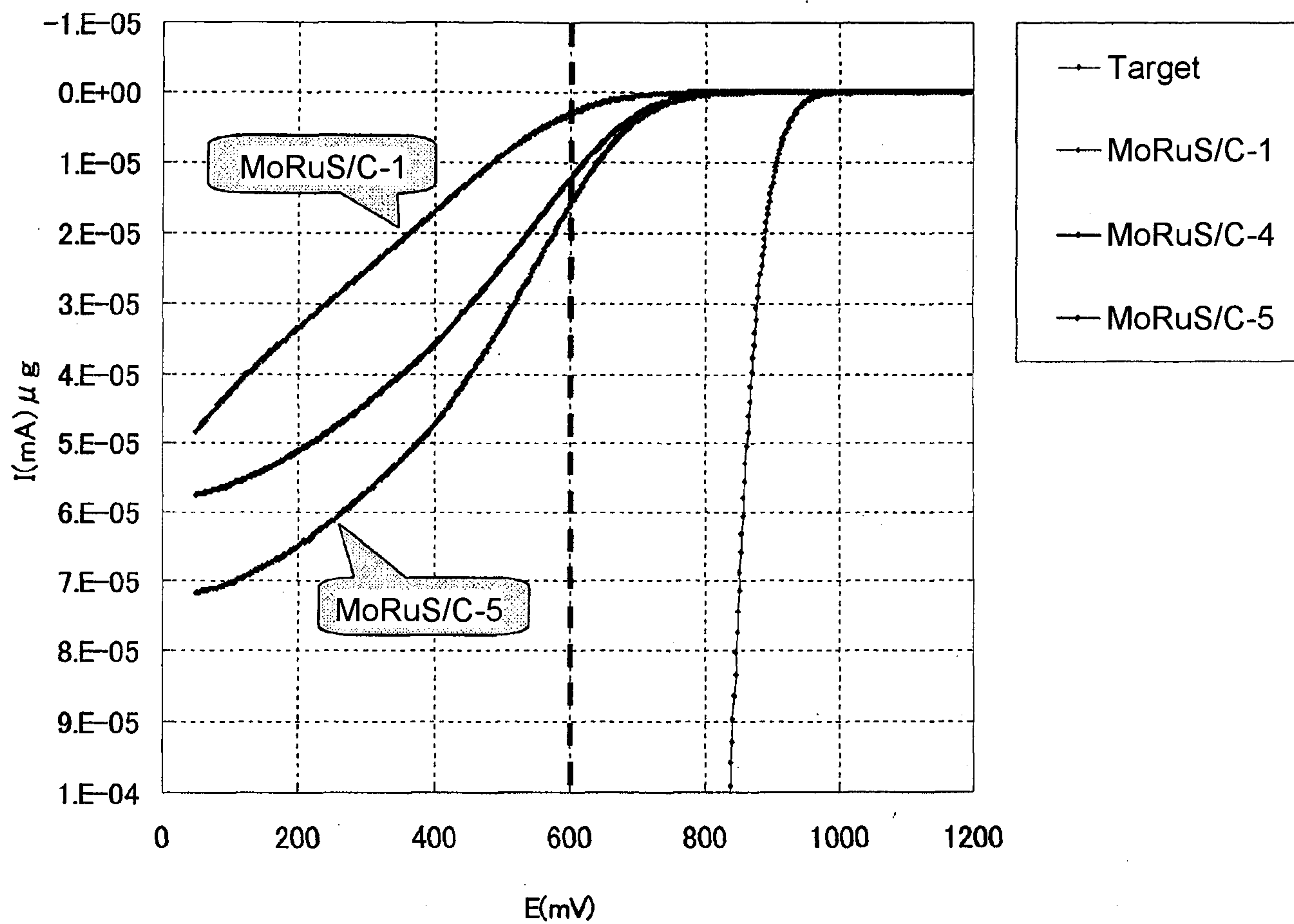


Fig. 56

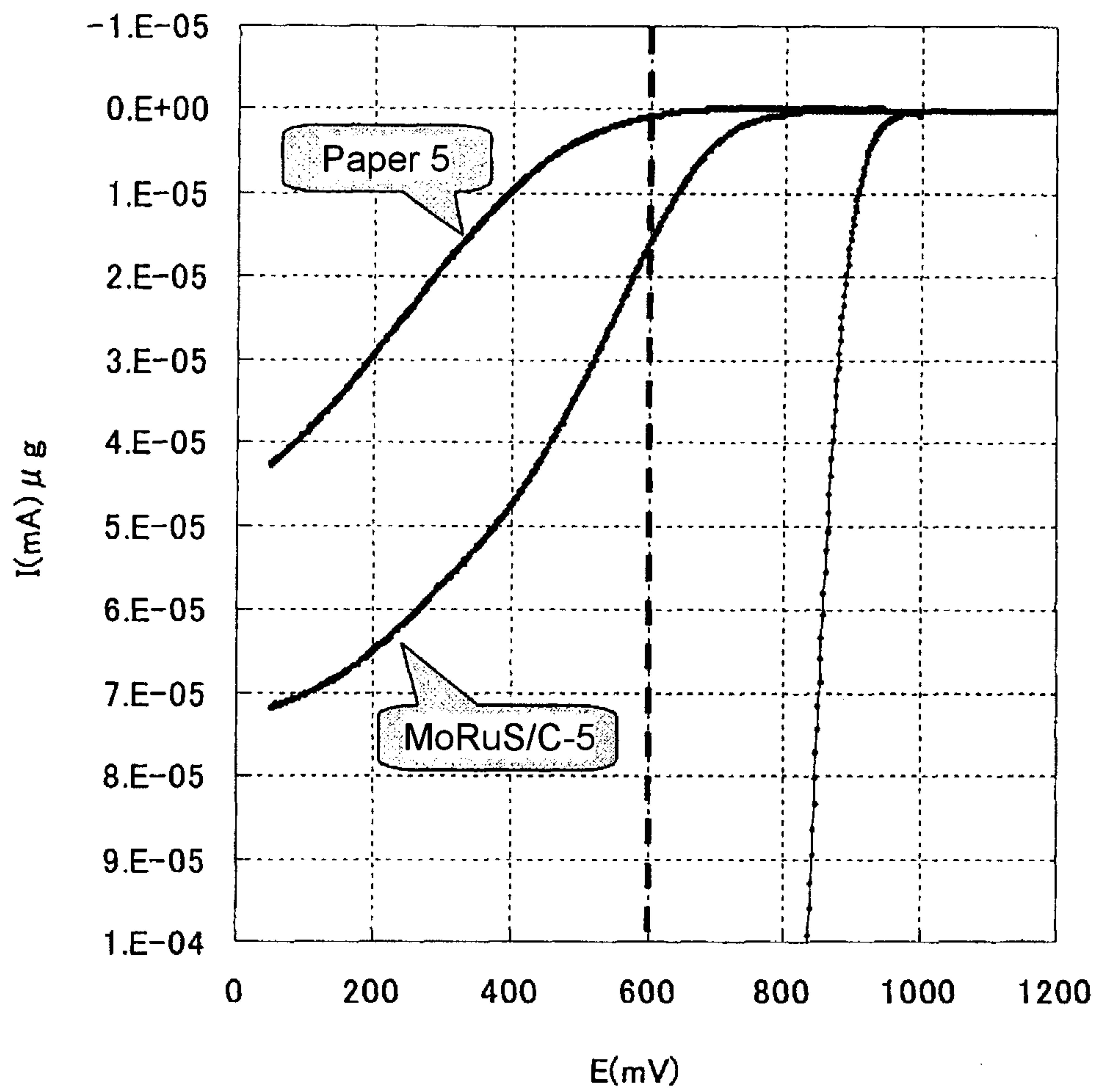


Fig. 57

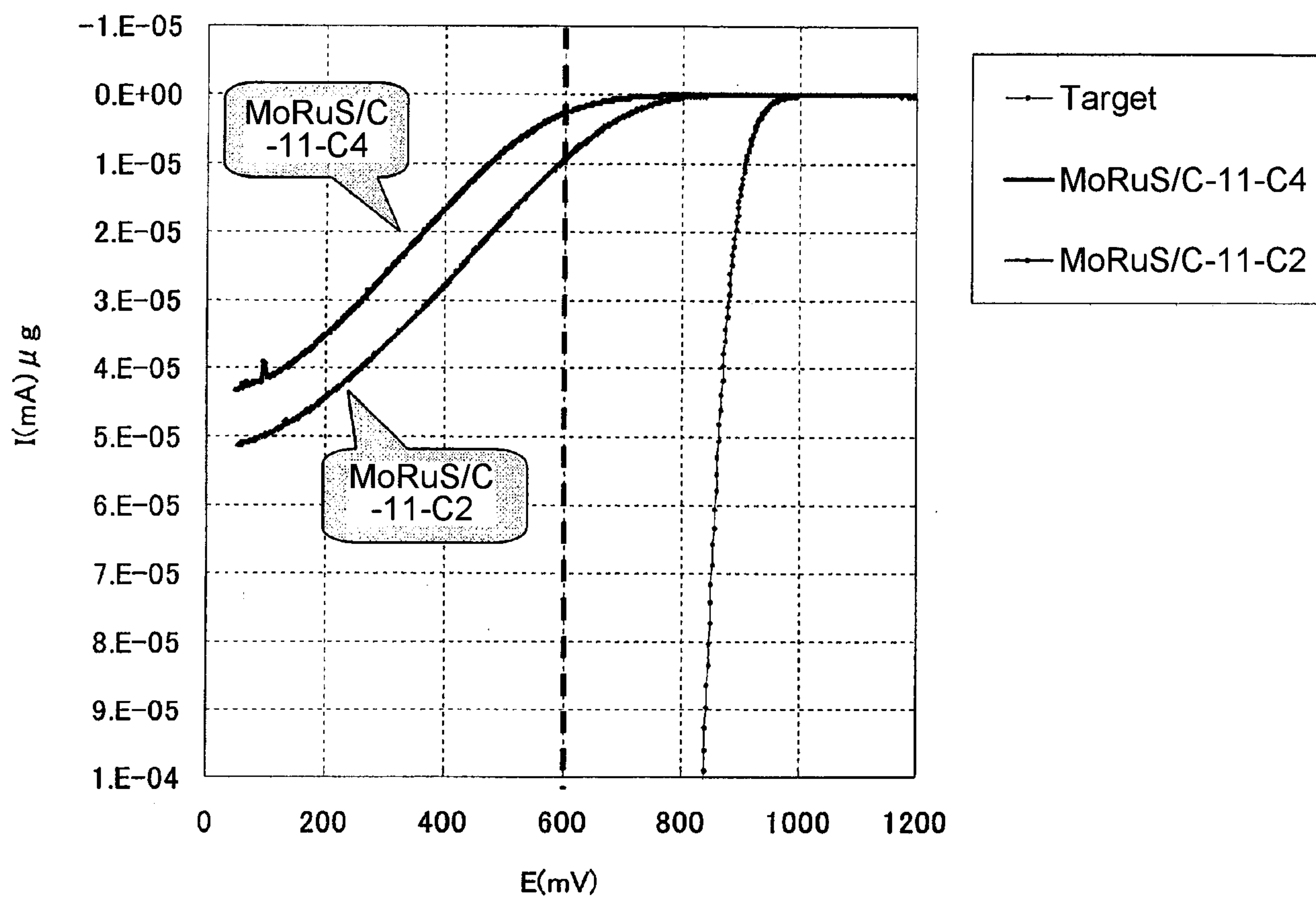


Fig. 58

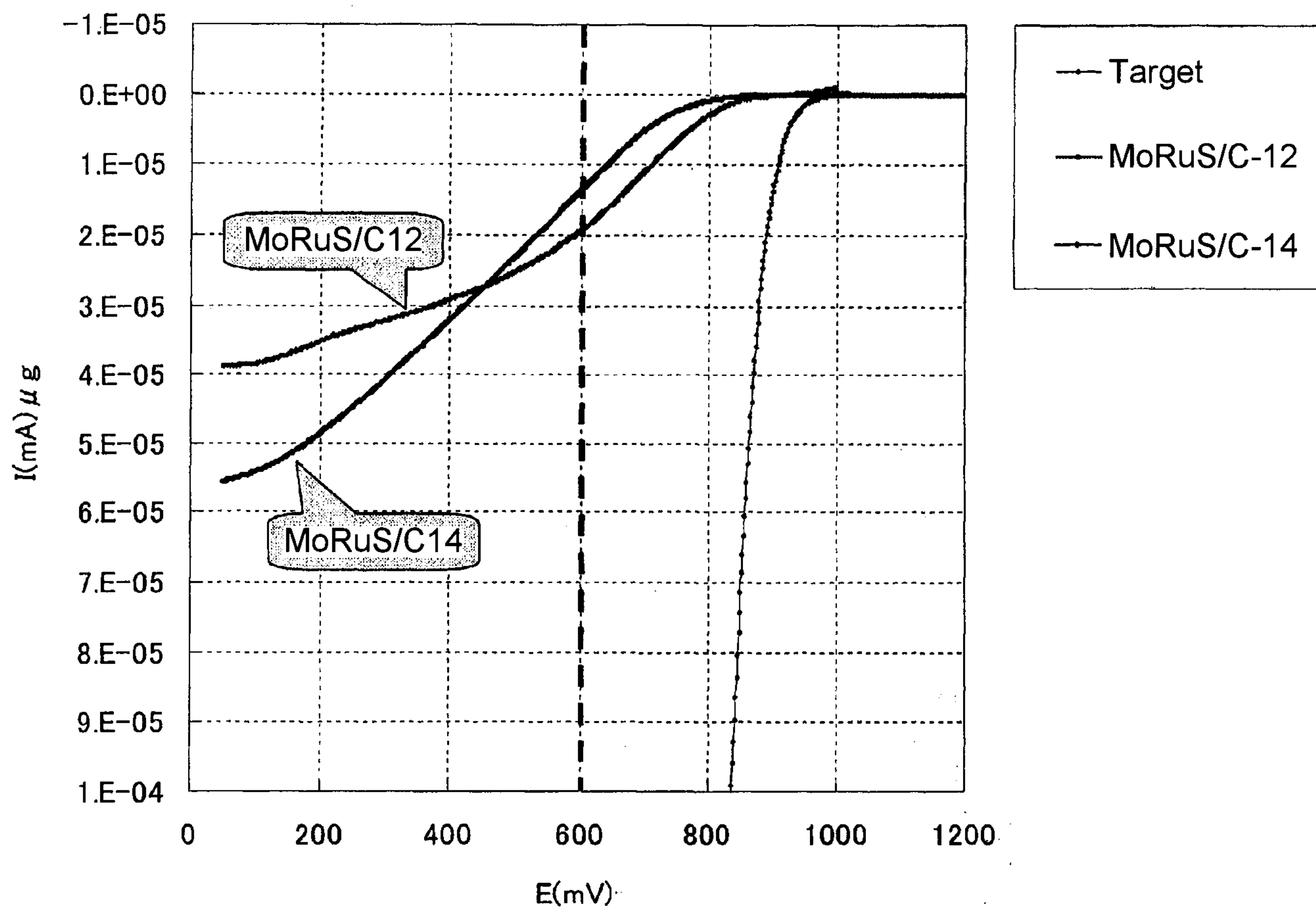


Fig. 59

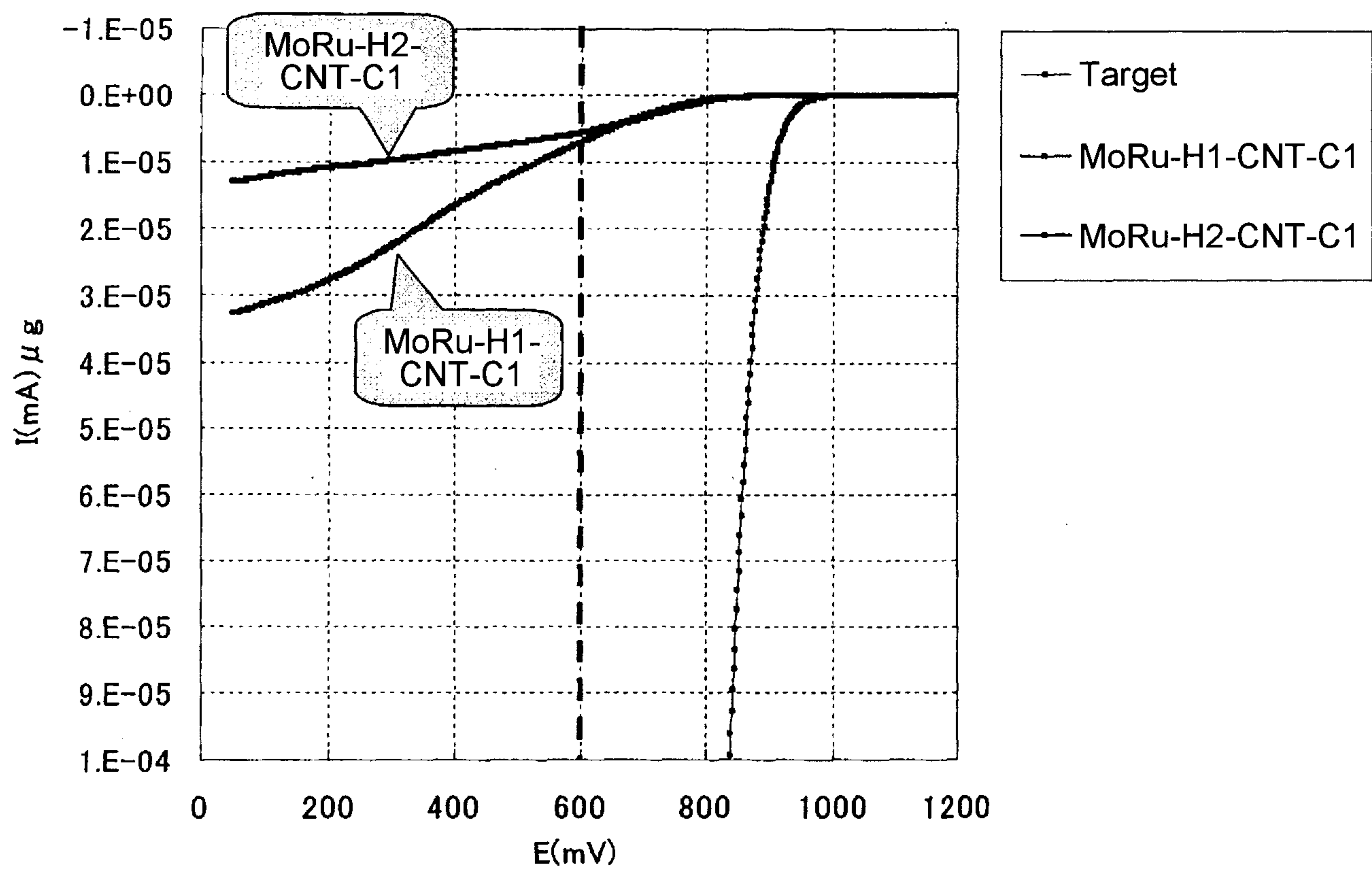


Fig. 61

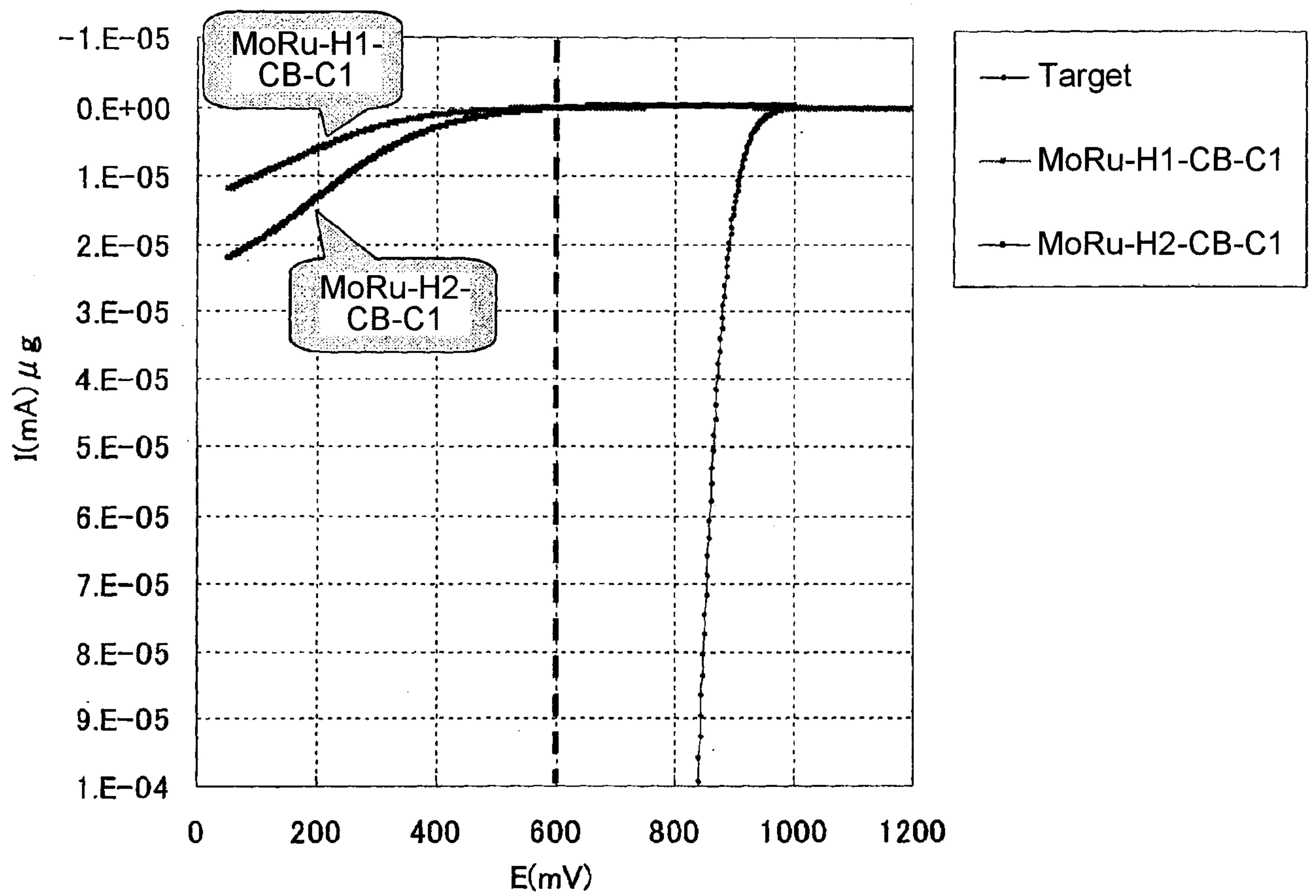


Fig. 62

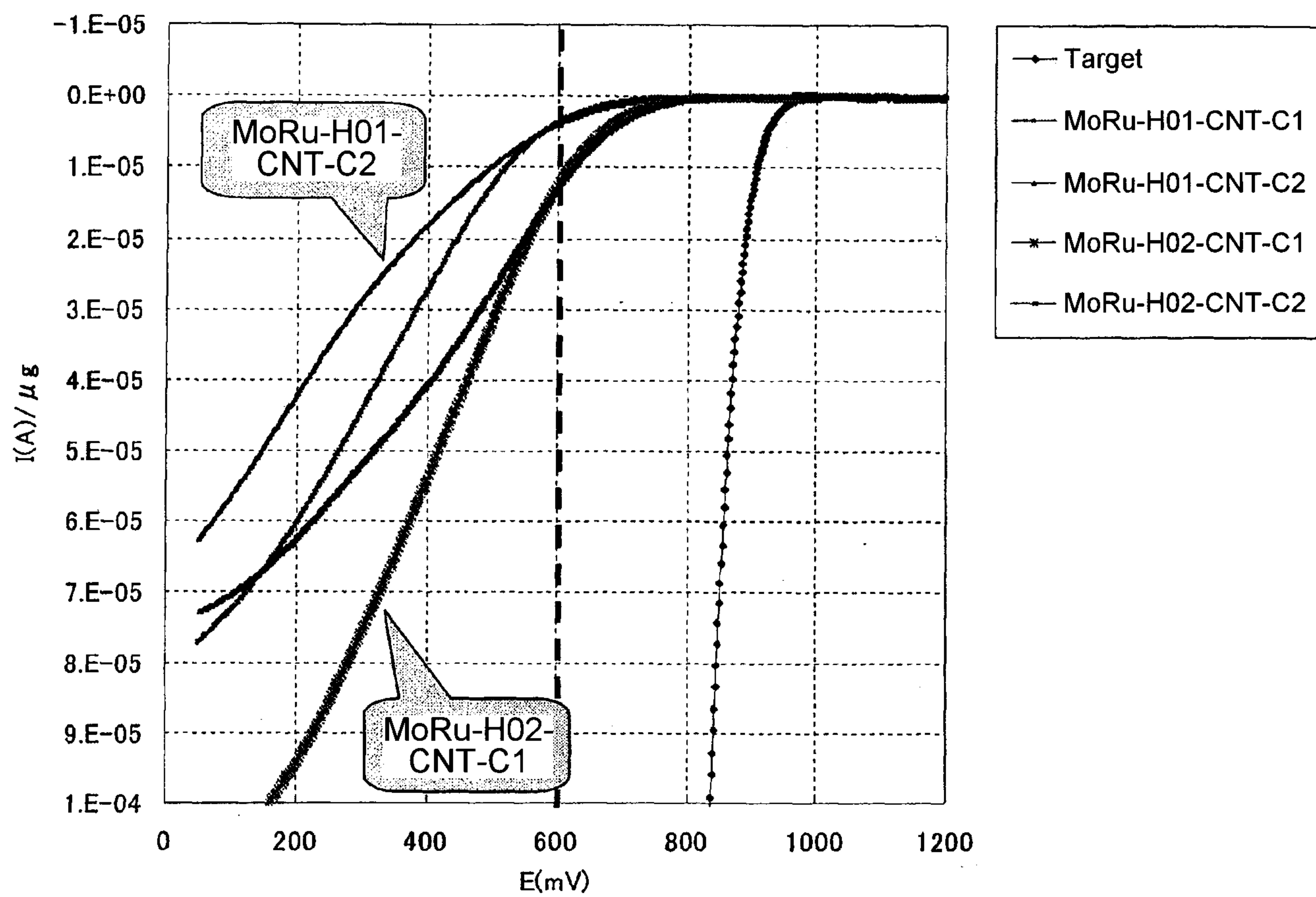
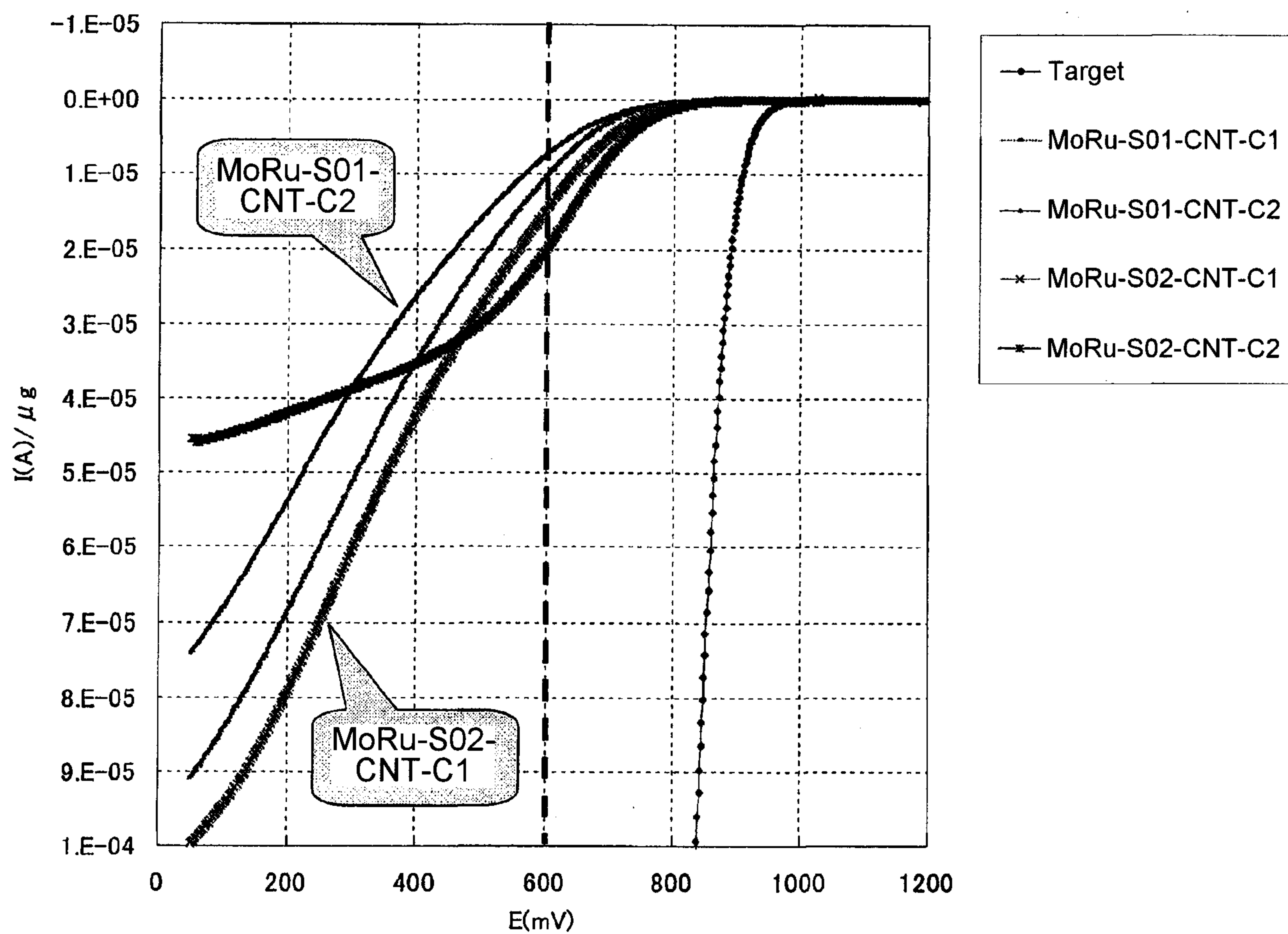


Fig. 63



Introduction of starting materials
(Mo, Ru, Rh, Re, and S) into autoclave
Types and quantitative ratios of
starting materials

Introduction of solvent into autoclave
Type and amount of solvent

Hydrothermal reaction
Solvothermal reaction

Washing, recovery via centrifugation, and
drying in vacuo of solid product

Presintering in Ar atmosphere
Temperature, duration

Evaluation of performance
SEM, HRTEM, EDX, FTIR, XRD