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(71) Demandeur/Applicant:
CLICK MATERIALS CORP., CA

(72) Inventeurs/Inventors:
BERLINGUETTE, CURTIS, CA;
HUDKINS, JESSE, CA;
DETTLEBACH, KEVAN, CA;
SALVATORE, DANIELLE, CA

(74) Agent: MBM INTELLECTUAL PROPERTY LAW LLP

(54) Titre : FILMS ELECTROCATALYTIQUES COMPRENANT DES METAUX OU OXYDES METALLIQUES AMORPHES
PREPARES PAR DECOMPOSITION DE PRECURSEURS PAR UN RAYONNEMENT DANS LE PROCHE
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(54) Title: ELECTROCATALYTIC FILMS COMPRISING AMORPHOUS METALS OR METAL-OXIDES PREPARED
USING NEAR-INFRARED DECOMPOSITION OF PRECURSORS

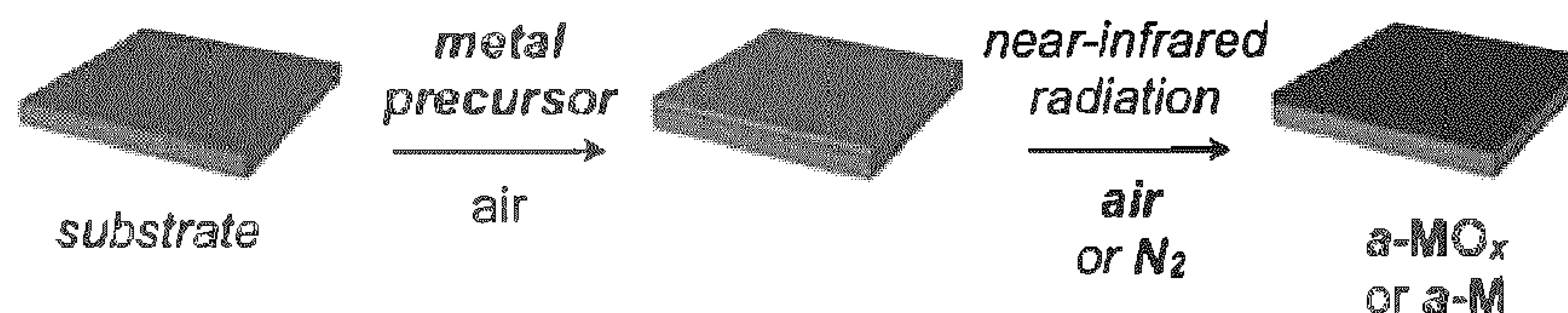


Fig. 1

(57) **Abrégé/Abstract:**

The present invention provides a method for making materials and electrocatalytic materials comprising amorphous metals or metal oxides. This method provides a scalable preparative approach for accessing state-of-the-art electrocatalyst films, as demonstrated herein for the electrolysis of water, and extends the scope of usable substrates to include those that are non-conducting and/or three-dimensional electrodes.

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(71) Applicant: FIREWATER FUEL CORP. [CA/CA]; 205 -
1211 14th Street SW, Calgary, Alberta T3C 1C4 (CA).(72) Inventor: BERLINGUETTE, Curtis; c/o FireWater Fuel
Corp., 205 - 1211 14th Street SW, Calgary, Alberta T3C
1C4 (CA).(74) Agent: MBM INTELLECTUAL PROPERTY LAW
LL[; 275 Slater St., 14th Floor, Ottawa, Ontario K1P 5H9
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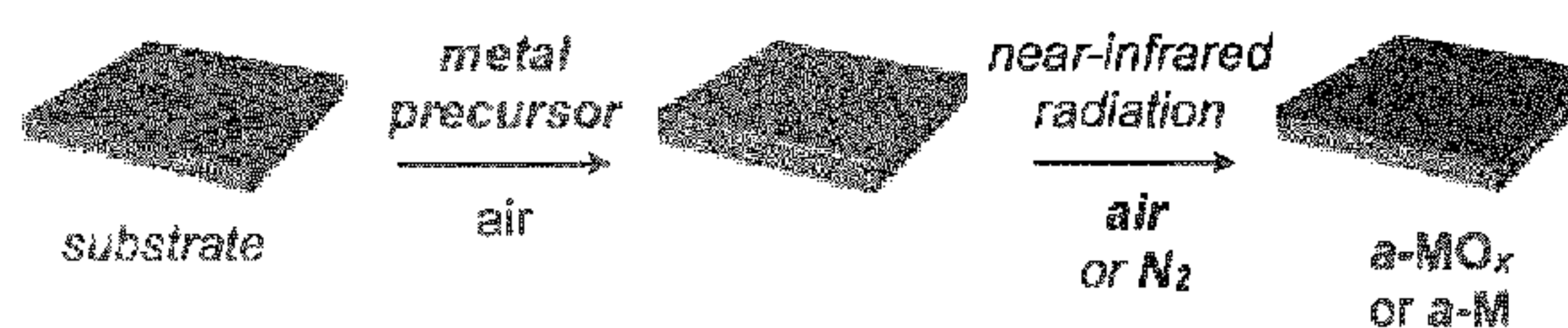
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Fig. 1

(57) Abstract: The present invention provides a method for making materials and electrocatalytic materials comprising amorphous metals or metal oxides. This method provides a scalable preparative approach for accessing state-of-the-art electrocatalyst films, as demonstrated herein for the electrolysis of water, and extends the scope of usable substrates to include those that are non- conducting and/or three-dimensional electrodes.

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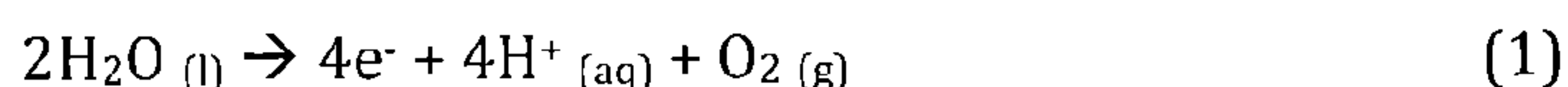
ELECTROCATALYTIC FILMS COMPRISING AMORPHOUS METALS OR METAL-OXIDES PREPARED USING NEAR-INFRARED DECOMPOSITION OF PRECURSORS

FIELD OF THE INVENTION

[0001] The present invention pertains to the field of metal-containing films and their uses, in particular films prepared using near-infrared radiation.

BACKGROUND

[0002] Amorphous metal and metal oxide films are pervasive in myriad applications [*e.g.*, transistors(1, 2), flexible electronics(3)], including schemes that involve the electrocatalytic oxidation of water into clean hydrogen fuels. Indeed, there is a growing body of evidence showing that amorphous metal oxides mediate the oxygen evolution reaction (OER; Eq. 1)(4-8) and hydrogen evolution reaction (HER; Eq. 2)(9, 10) more efficiently than crystalline phases of the same compositions.



[0003] These findings are particularly important in the context of efficiently storing electricity produced from intermittent and variable renewable energy sources (*e.g.*, sunlight, wind) as high density fuels (*e.g.*, hydrogen) (11, 12).

[0004] The majority of amorphous metal oxide films reported in the literature are formed by electrodeposition(4-7), sputtering(13), thermal decomposition(3, 14), or ultra-violet-light-driven decomposition(8) of metal precursors.

[0005] Films prepared by these methods can demonstrate state-of-the-art electrocatalytic OER activities(15-20), the syntheses are not necessarily amenable to scalable manufacture due to sensitivities to metal work functions, reaction media, or prohibitively expensive precursors.

[0006] Consequently, accessing amorphous compositions of many metal oxides for commercial applications is not trivial, particularly when complex metal compositions are desired(3, 8).

[0007] The isolation of amorphous metals is substantially more challenging, as single-element metallic films typically require sophisticated protocols(21).

[0008] There is therefore a need for processes for the formation of amorphous metal-containing films under moderate conditions.

SUMMARY OF THE INVENTION

[0009] An object of the present invention is to provide a process for near-infrared-driven decomposition of metal precursors for the formation of amorphous metal and metal oxide films. In accordance with an aspect of the present invention, there is provided a process for forming an amorphous metal-containing electrocatalytic film, the process comprising the steps of: a) providing a substrate; b) coating the substrate with a metal precursor solution; and c) exposing the coated substrate to near-infrared radiation to form the amorphous metal-containing film.

[0010] In accordance with another aspect of the present invention, there is provided an electrocatalytic material suitable for use in electrocatalysis formed by the process in accordance with the present invention.

BRIEF DESCRIPTION OF THE FIGURES

[0011] Figure 1 is a schematic representation of the NIRDD of a metal precursor on a substrate leading to the formation of amorphous metal oxide (α -MO_x) and reduced metal (α -M) films under air and nitrogen, respectively, in accordance with the present invention.

[0012] Figures 2A and B illustrate cyclic voltammograms for thin films of (A) α -FeO_x and (B) α -Fe on FTO, prepared in accordance with the present invention.

[0013] Figures 3A and B illustrate FTIR spectra for thin films of Fe(eh)₃ on FTO upon exposure to NIR radiation for (A) 0, 4, 16, 32 and 64 min in air, and (B) 0 and 60 min under nitrogen.

[0014] Figures 4A and B illustrate the fitting of the copper $2p_{3/2}$ region of X-ray photoelectron spectra recorded on thin films of $\text{Cu}(\text{eh})_2$ on FTO after being subjected to the NIRRD process under (A) air and (B) nitrogen, respectively, in accordance with the present invention.

[0015] Figure 5 illustrates temperature profiles of FeCl_3/FTO , $\text{Fe}(\text{eh})_3/\text{FTO}$ and bare FTO.

[0016] Figures 6A and B illustrate UV-vis absorption spectra, before and after being subjected to the NIRDD process of the present invention, of: (A) various metal halide precursor complexes on glass and (B) various coordination complexes on glass.

[0017] Figures 7A and B illustrate powder XRD patterns acquired on as-prepared and annealed ($T_{\text{anneal}} = 500\text{ }^\circ\text{C}$) $\alpha\text{-FeO}_x$ and $\alpha\text{-Fe}$ films prepared by applying the NIRDD process of the present invention to (A) FeCl_3 and (B) $\text{Fe}(\text{eh})_3$ deposited on FTO under air and nitrogen, respectively.

[0018] Figure 8 illustrates cyclic voltammograms for thin films of $\alpha\text{-FeO}_x$, prepared by the NIRDD process in air, and the respective precursor films from which they were derived.

[0019] Figures 9A-C illustrate powder XRD patterns acquired on as-prepared films of (A) $\alpha\text{-IrO}_x$, (B) $\alpha\text{-NiO}_x$ and (C) $\alpha\text{-MnO}_x$ on FTO.

[0020] Figure 10 illustrates cyclic voltammograms recorded on thin films of $\alpha\text{-IrO}_x$, $\alpha\text{-NiO}_x$, $\alpha\text{-MnO}_x$ and $\alpha\text{-Fe}_2\text{Ni}_3\text{O}_x$ on FTO.

[0021] Figures 11A and B illustrate Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) profiles for (A) FeCl_3 and (B) $\text{Fe}(\text{eh})_3$ under air and N_2 at a ramp rate of $10\text{ }^\circ\text{C min}^{-1}$.

[0022] Figures 12A and B illustrate TGA and DSC profiles for (A) FeCl_3 and (B) $\text{Fe}(\text{eh})_3$ brought to $200\text{ }^\circ\text{C}$ and then held for 60 min.

[0023] Figures 13A-C illustrate FTIR spectra of independent samples of $\text{Fe}(\text{eh})_3/\text{FTO}$ before and after (A) exposure to NIR radiation for 30 min, (B) heating at 200°C in a furnace for 30 min, (C) heating at 250°C in a furnace for 30 min.

[0024] Figure 14 illustrates FTIR spectra of thin films of Ir(acac)₃/FTO, Ni(eh)₂/FTO, and Mn(eh)₃/FTO subjected to the NIRDD process in accordance with the present invention for varying periods of time.

[0025] Figures 15A-C illustrate X-ray photoelectron spectra for α -FeO_x and α -Fe on FTO.

[0026] Figures 16A and B illustrate X-ray photoelectron spectra detailing the Fe 2p_{3/2} region. Sums of the fitting components for (A) α -FeO_x and (B) α -Fe are shown in red.

[0027] Figures 17A-C illustrate XPS data for α -CuO_x and α -Cu on FTO.

[0028] Figures 18A-C illustrate images of solid samples of (A) Cu(ch)₂, (B) Cu(eh)₂ subjected to NIRDD under nitrogen, and (C) Cu(eh)₂ subjected to NIRDD under air, in accordance with the present invention.

[0029] Figures 19A and B illustrate powder XRD patterns acquired on as-prepared and annealed ($T_{\text{anneal}} = 500$ °C) α -CuO_x and α -Cu films prepared from Cu(eh)₂ under (A) air and (B) nitrogen.

[0030] Figures 20A and B illustrate FTIR spectra of Fe₂Ni₃(eh)₃/FTO subjected to NIRDD for the times indicated under (A) air and (B) nitrogen to highlight the progressive loss in intensity of the bands associated with the ligand.

[0031] Figures 21A and B illustrate powder XRD patterns acquired on as-prepared films of (A) α -Fe₂Ni₃O_x and (B) α -Fe₂Ni₃ on FTO recorded under air and nitrogen, respectively.

[0032] Figures 22A and B illustrate cyclic voltammograms for thin films of (A) α -Fe₂Ni₃O_x and (B) α -Fe₂Ni₃ prepared by NIRDD under air and N₂, respectively.

[0033] Figure 23A illustrates cyclic voltammograms for thin films of α -IrO_x/membrane, IrCl₃/membrane, and the membrane, where the membrane is Nafion[®]. Figure 23B illustrates a membrane electrode assembly.

[0034] Figures 24A and B illustrate (A) full and (B) expanded FTIR spectra of Ir(acac)₃/membrane subjected to NIR radiation for 0 and 60 min. A trace for untreated Nafion membrane is also shown.

[0035] Figure 25 is a scanning electron microscope (SEM) image of FeO_x prepared in accordance with one embodiment of the present invention.

[0036] Figure 26 illustrates an SEM image of NiO_x prepared in accordance with one embodiment of the present invention.

[0037] Figure 27 illustrates an SEM image of CoO_x prepared in accordance with one embodiment of the present invention.

[0038] Figure 28 illustrates an SEM image of IrO_x prepared in accordance with one embodiment of the present invention.

[0039] Figure 29 illustrates an SEM image of FeO_x prepared in accordance with one embodiment of the present invention.

[0040] Figure 30 illustrates an SEM image of RuO_x prepared in accordance with one embodiment of the present invention.

[0041] Figure 31 illustrates an SEM image of CuO_x prepared in accordance with one embodiment of the present invention.

[0042] Figure 32 depicts images of amorphous mixed metal and mixed metal oxide films prepared in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0043] The present disclosure relates to a new process for generating thin films of amorphous metals and metal oxides through the exposure of transition metal precursors (*e.g.*, a metal salt or a metal coordination complex) to near-infrared (NIR) radiation under inert and aerobic environments, respectively. Figure 1 is a schematic representation of the NIR-driven decomposition (NIRDD) of a metal precursor on a substrate leading to the formation of amorphous metal oxide ($\alpha\text{-MO}_x$) and reduced metal ($\alpha\text{-M}$) films under air and nitrogen, respectively. Not only does this NIRDD process furnish amorphous metal oxide films that display properties commensurate with films prepared by more complex methods and precursors, it is compatible with curing techniques widely used in large-scale manufacturing

processes, including roll-to-roll processing (22, 23). The NIRDD method therefore provides unprecedented access to amorphous phases of reduced metals and alloys using moderate experimental conditions.

[0044] The finding that amorphous metal or metal oxide films can be prepared by merely exposing metal precursors (*e.g.*, a metal salt or a metal coordination complex) coated on a substrate to NIR radiation represents an important breakthrough for the scalable manufacture of state-of-the-art electrocatalysts and other thin-film applications.

[0045] The NIRDD process of the present invention provides easy access to complex compositions of alloys and metal oxide films in the amorphous phases, on a much broader substrate scope than is available to other commonly used methods.

[0046] In embodiments of the invention, the amorphous metal-containing film is an amorphous metal oxide, an amorphous mixed metal oxide, an amorphous metal, or an amorphous mixed metal.

[0047] In accordance with the present invention, the amorphous metal-containing film comprises a metal which is selected from any transition metal. In preferred embodiments of the present invention, the metal is selected from iron, iridium, manganese, nickel, copper, ruthenium, cobalt, tungsten, indium, tin, molybdenum or any combination thereof. Also suitable for use in the present invention are metals from Groups 1 to 12, Rows 2 to 6, and any element from Groups 13 to 16, Rows 2 to 6.

[0048] In one embodiment, the metal precursor solution is a solution of a metal salt. Nonlimiting examples of suitable metal salts include MCl_x or $M(NO_3)_x$, where M is a metal selected from iron, iridium, manganese, nickel, copper, ruthenium, cobalt, tungsten, indium, tin, molybdenum or any combination thereof, and x is an integer from 1 to 6. Accordingly, nonlimiting examples of suitable metal precursors include $FeCl_3$, $Fe(NO_3)_3$, $IrCl_3$, $NiCl_2$, $Ni(NO_3)_2$, Fe_2Ni_3Cl , $CoCl_2$, $RuCl_3$, $CuCl_2$, and WCl_6 .

[0049] In one embodiment, the metal precursor solution is a solution of a metal coordination complex. Nonlimiting examples of ligands suitable for use in the metal coordination complexes are 2-ethylhexanoate ligands [eh] or acetylacetonate [acac] ligands. Accordingly, nonlimiting examples of suitable metal precursors include $Fe(eh)_3$, $Cu(eh)_2$, $Ir(acac)_3$, $Ni(eh)_2$, $Mn(eh)_3$, $Co(eh)_2$, $Mo(eh)_2$, $Sn(eh)_2$, $In(acac)_3$, and $Fe_2Ni_3(eh)_3$.

[0050] In one embodiment, the process is carried out in an inert atmosphere such as nitrogen, or any other inert, non-oxidizing gas, which favorably allows for the formation of amorphous metal or amorphous mixed metal (or metal alloy) films. Accordingly, nonlimiting examples of amorphous metal-containing films which can be obtained using the process of the present invention include α -Fe, α -Cu, α -Fe₂Ni₃, α -Ni, and α -Mn.

[0051] In one embodiment, the process is carried out in an oxidizing (*i.e.*, oxygen containing) atmosphere (*e.g.*, air), which favorably allows for the formation of amorphous metal oxide or mixed metal oxide films. Accordingly, nonlimiting examples of amorphous metal oxide or mixed metal oxide films which can be obtained using the process of the present invention include α -FeO_x, α -IrO_x, α -NiO_x, α -MnO_x, α -Fe₂Ni₃O_x, α -CuO_x, α -CoO_x, α -MoO_x, α -SnO_x, α -InO_x, α -RuO_x, and α -WO_x.

[0052] The process of the present invention allows for the formation of amorphous metal-containing films on a wide variety of substrates. Nonlimiting examples of suitable substrates include glass, fluorine-doped tin oxide-coated glass (FTO), synthetic polymers (*e.g.* Nafion®), metallic substrates (*e.g.*, nickel, platinum, gold, silver, copper or titanium), plastic, glassy carbon and stainless steel.

[0053] In one embodiment, the process for forming an amorphous metal-containing film for use in electrocatalysis further comprises a step of tuning the properties of the electrocatalyst. In one embodiment, the tuning step comprises annealing the metal oxide film.

[0054] The NIRDD process of the present invention is also easy to scale on the basis that the infrastructure requirements are similar to curing processes currently used in industry (22, 23).

[0055] In addition, the NIRDD fabrication process is also compatible with substrates that are non-conducting, three-dimensional, and sensitive to temperature and UV radiation, for example, Nafion®. In accordance with the present invention, the process allows the formation of an amorphous metal-containing film on a substrate, thereby providing a material suitable for use in electrocatalysis.

[0056] The NIRDD process of the present invention can be used for the formation of amorphous (oxide) films containing metals of relevance to the OER reaction [*e.g.*, iron (7, 8), iridium (18, 24), manganese (6, 25), nickel (7, 8, 26), copper (27, 28)].

EXAMPLES

Example 1 - Novel Synthesis of Metal Oxides (MO_x) using IR Irradiation

[0057] The formation of amorphous metal oxide films upon exposure of metal salts to NIR radiation was confirmed by placing $FeCl_3$ spin-cast on FTO, $FeCl_3/FTO$, under a 175-W NIR lamp for 120 min in an aerobic environment. The color change from yellow to light brown upon irradiation supported the formation of iron oxide (UV-vis spectra are provided in Fig. 6), while the absence of reflections in the powder XRD patterns indicated the amorphous nature of the material (Fig. 7). Figure 7 illustrates powder XRD patterns acquired on as-prepared and annealed ($T_{anneal} = 500\text{ }^{\circ}C$) α - FeO_x and α -Fe films prepared by applying the NIRDD process to (A) $FeCl_3$ and (B) $Fe(eh)_3$ deposited on FTO under air and nitrogen, respectively. Data recorded on a bare FTO substrate is also provided. *Inset*: Expanded view highlighting the region where the reflection associated with the maghemite and hematite form of Fe_2O_3 at 35.5° is observed. This reflection is observed only for the films annealed at $500\text{ }^{\circ}C$ under air, denoted FeO_x -annealed. (A signature Bragg reflection of hematite is apparent at $2\theta = 35.9^{\circ}$ only after annealing the same film in air for 1 h at $500\text{ }^{\circ}C$.) Figure 6 illustrates UV-vis absorption spectra, before and after being subjected to the NIRDD process, of: (A) metal halide precursor complexes on glass, $FeCl_3/glass$ (1), $NiCl_2/glass$ (2), and $Fe_2Ni_3Cl/glass$ (3); and (B) coordination complexes on glass, $Fe(eh)_3/glass$ (1), $Ni(eh)_3/glass$ (2), $Fe_2Ni_3(eh)_3/glass$ (3), $Ir(acac)_3/glass$ (4) and $Mn(eh)_3/glass$ (5). Data for $FeCl_3/glass$ and $Fe(eh)_3/glass$ following the NIRDD process in a nitrogen environment is indicated by “1/ N_2 ”, respectively. The glass background is also shown. Note that glass was used rather than FTO to avoid interference at longer wavelengths. The film $Fe_2Ni_3Cl/glass$ was prepared from a solution of 2 g of deionized water containing $NiCl_2$ (0.088 g) and $FeCl_3$ (0.039 g) that was spin-cast onto a glass substrate.

[0058] Figure 29 is an SEM image of FeO_x prepared according to this process.

[0059] The electrochemical behavior of this amorphous film, α - FeO_x , in aqueous media was also consistent with previous accounts of amorphous iron oxide (Fig. 2, Table 1). Figure 2 illustrates cyclic voltammograms for thin films of α - FeO_x (Figure 2A) and α -Fe (Figure 2B) on FTO. Values indicate the sequence of the cycles that were recorded (experimental

conditions: counter-electrode = Pt mesh; reference electrode = Ag/AgCl, KCl (sat'd); scan rate = 10 mV s^{-1} ; electrolyte = 0.1 M KOH (aq)). Importantly, an extensive electrochemical analysis indicated that $\alpha\text{-FeO}_x$ could be readily produced from other iron compounds [e.g., $\text{Fe(NO}_3)_3$, Fe(eh)_3 ; eh = 2-ethylhexanoate] (Fig. 8), and that the NIRDD method translated effectively to other metals: Films of $\alpha\text{-IrO}_x$, $\alpha\text{-NiO}_x$, and $\alpha\text{-MnO}_x$ were also formed when the corresponding metal compounds were subjected to NIR radiation (Figs. 9 and 10). The electrocatalytic properties of $\alpha\text{-IrO}_x$ in $1 \text{ M H}_2\text{SO}_4$ (Fig. 10), a rare acid-stable OER catalyst, are consistent with literature values, as are those for $\alpha\text{-NiO}_x$ and $\alpha\text{-MnO}_x$, OER electrocatalysts pervasive in the contemporary literature owing to their high activities and high natural abundances, in alkaline conditions (Table 1). Figure 8 illustrates cyclic voltammograms for thin films of $\alpha\text{-FeO}_x$, prepared by the NIRDD process in air, and the respective precursor films from which they were derived from; $\text{Fe(NO}_3)_3$, FeCl_3 and Fe(eh)_3 precursors. All data is collected on films deposited on FTO, and thus the slight differences in the response of the $\alpha\text{-FeO}_x$ films are attributed to minor differences in film roughness or film densities. Electrochemistry conditions: counterelectrode = Pt mesh; reference electrode = Ag/AgCl, KCl (sat'd); scan rate = 10 mV s^{-1} ; electrolyte = $0.1 \text{ M KOH}_{(\text{aq})}$; current densities were corrected for uncompensated resistance. Figure 9 illustrates powder XRD patterns acquired on as-prepared films of (A) $\alpha\text{-IrO}_x$, (B) $\alpha\text{-NiO}_x$ and (C) $\alpha\text{-MnO}_x$ on FTO. No reflections are observed other than those associated with FTO. Figure 10 illustrates cyclic voltammograms recorded on thin films of $\alpha\text{-IrO}_x$, $\alpha\text{-NiO}_x$, $\alpha\text{-MnO}_x$ and $\alpha\text{-Fe}_2\text{Ni}_3\text{O}_x$ on FTO. Data recorded on bare FTO is also shown. Electrochemistry conditions: counterelectrode = Pt mesh; reference electrode = Ag/AgCl, KCl (sat'd); scan rate = 10 mV s^{-1} ; electrolyte = $1 \text{ M H}_2\text{SO}_4_{(\text{aq})}$ for $\alpha\text{-IrO}_x$, or $0.1 \text{ M KOH}_{(\text{aq})}$ for $\alpha\text{-NiO}_x$, $\alpha\text{-MnO}_x$, $\alpha\text{-Fe}_2\text{Ni}_3\text{O}_x$ and bare FTO. Current densities were corrected for uncompensated resistance.

Table 1. Benchmarked OER Activities of $\alpha\text{-MO}_x$ Films.

sample*	onset η (V vs RHE)	Tafel slope (mV dec ⁻¹)	$\eta_{10 \text{ mA/cm}^2}$ (V) [†]	
			this work	literature
$\alpha\text{-FeO}_x$	0.32	35	0.42 0.24 [‡]	- 0.40 [‡] (16)

α -NiO _x	0.21	62	0.36	0.36 (15)
α -Fe ₂ Ni ₃ O _x	0.19	34	0.33	0.35 [§] (15)
α -MnO _x	0.22	167	0.43 [‡]	0.56 [‡] (16)
α -IrO _x	0.08	47	0.26	0.26 (15)

^{*}O_x is broadly defined as oxo/oxyl/hydroxo. [†]Overpotential required to reach 10 mA/cm², unless otherwise indicated, without correcting for mass transport. [‡]Overpotential required to reach 1 mA/cm²; we are not aware of any value reported at 10 mA/cm². [§]Corresponds to FeNiO_x. All potentials in this manuscript are expressed versus a reversible hydrogen electrode, RHE.

[0060] The discovery that NIRDD could drive α -MO_x formation was not expected given the low absorptivity of the films at $\lambda > 600$ nm (Fig. 6). It is therefore contended that the efficacy of the process is due to localized heating of the film rather than a photochemical effect.

[0061] This assessment is validated by the observations that: (i) substrates do not exceed 200 °C under the present experimental conditions (Fig. 5); (ii) bulk samples of FeCl₃ do not decompose to a mass corresponding to Fe₂O₃ until >300 °C (Figs. 11 and 12); (iii) samples of precursors on FTO exposed to 1 h of constant irradiation yielded complete decomposition, while six successive 10-min segments of exposure separated by 5-min periods in the dark did not; and (iv) films of precursors on FTO did not show the same rates of decomposition when placed in an oven set at 200 °C (Fig. 13). Figure 5 illustrates temperature profiles of FeCl₃/FTO, Fe(eh)₃/FTO and bare FTO. Additional control measurements were also collected on a sample where Fe(eh)₃ deposited directly on the copper wire of the thermocouple by the NIRDD process, denoted Fe(eh)₃/thermocouple, as well as the bare wire of the thermocouple. Temperature readings were recorded with a thermocouple in 5-min increments, and indicated a rise in temperature that plateaus at a value no greater than 175 °C. These collective results confirm that a substrate temperature of 200 °C is not reached during a constant 1 h exposure to NIR radiation under the present experimental conditions.

[0062] Figure 11 illustrates TGA and DSC profiles for (A) FeCl₃ and (B) Fe(eh)₃ under air and N₂ at a ramp rate of 10 °C min⁻¹. The bottom plots overlay the respective percent-mass-loss profiles in air and N₂ to highlight the effect of the atmospheric environment. Both FeCl₃ and Fe(eh)₃ appear to lose ligands in a stepwise fashion; our tentative

assignments indicate that the first ligand is excluded at $\sim 200^\circ\text{C}$ and the last ligand is liberated at $\sim 400^\circ\text{C}$. The ligands are excluded from FeCl_3 in three distinct steps in both air and N_2 , while data recorded on $\text{Fe}(\text{eh})_3$ in air shows the loss of two ligands in quick succession followed by the loss of the third ligand at higher temperatures; this pattern is reversed under nitrogen. Complete decomposition is not complete until $T > 400^\circ\text{C}$ for any of the data shown, which is much higher than the surface temperatures reached during the NIRDD process. Figure 12 illustrates TGA and DSC profiles for (A) FeCl_3 and (B) $\text{Fe}(\text{eh})_3$ brought to 200°C and then held for 60 min. The FeCl_3 and $\text{Fe}(\text{eh})_3$ precursor complexes do not decompose fully to a final mass of Fe_2O_3 during this period. Both measurements were recorded in an aerobic environment. Figure 13 illustrates FTIR spectra of independent samples of $\text{Fe}(\text{eh})_3/\text{FTO}$ before and after (A) exposure to NIR radiation for 30 min, (B) heating at 200°C in a furnace for 30 min, (C) heating at 250°C in a furnace for 30 min.

[0063] The temporal resolution of the NIRDD process was evaluated by tracking the formation of $\alpha\text{-FeO}_x$ during the NIR-irradiation of $\text{Fe}(\text{eh})_3$, which contains ligands that can be tracked by FTIR spectroscopy (17, 29), and indicated complete ligand loss within 1 h in both air and N_2 (Fig. 3). Figure 3 illustrates FTIR spectra for thin films of $\text{Fe}(\text{eh})_3$ on FTO upon exposure to NIR radiation for (A) 0, 4, 16, 32 and 64 min in air, and (B) 0 and 60 min under nitrogen. Arrows indicate trends in the intensities of the C-H and C-O vibrational modes of 2-ethylhexanoate.(8). [The absorption spectra (Fig. 6), lack of powder XRD reflections (Fig. 7), and electrochemical data (Table 1) collectively support the assignment of the resultant films as $\alpha\text{-FeO}_x$.] Films of $\alpha\text{-MO}_x$ ($M = \text{Ir}, \text{Ni}, \text{Mn}$) derived from $\text{Ir}(\text{acac})_3$ ($\text{acac} = \text{acetylacetonate}$), $\text{Ni}(\text{eh})_2$, and $\text{Mn}(\text{eh})_2$, respectively, were formed quantitatively within four hours of irradiation (Fig. 14). Figure 14 illustrates FTIR spectra of thin films of $\text{Ir}(\text{acac})_3/\text{FTO}$, $\text{Ni}(\text{eh})_2/\text{FTO}$, and $\text{Mn}(\text{eh})_3/\text{FTO}$ for 0, 4, 16, 64, 128, and 256 min subjected to the NIRDD process showing the progressive loss of ligands in <2 h. Absorption bands are associated with the symmetric and asymmetric vibrations of the C-O groups of the 2-ethylhexanoate ligand and free acid.

Example 2 - Novel Synthesis of Metals (M) using IR Irradiation under Inert Atmosphere

[0064] The formation of α -FeO_x from FeCl₃ signaled that oxygen in the films was sourced from the aerobic environment, thus raising the possibility that more reduced forms of amorphous films could be accessed by carrying out NIRDD in an inert atmosphere.

[0065] This hypothesis was tested by irradiating a film of FeCl₃ on FTO under nitrogen, which yielded a light grey film, denoted α -Fe, that did not produce any Bragg reflections (Fig. 7). Moreover, the electrochemistry of α -Fe on FTO in 0.1 M KOH_(aq) was consistent with a lower average iron valency than that of α -FeO_x (Fig. 2). An oxidative sweep of α -FeO_x leads to a sharp rise in current at 1.55 V coincident with catalytic OER (Fig. 2A), and subsequent cycles over the 1.0-1.8 V range led to superimposable traces. The oxidative sweep for α -Fe featured a markedly different current profile (Fig. 2B); however, subsequent cycles indicated α -Fe was converted to α -FeO_x upon oxidation in aqueous media on the basis of the superimposable scans. The differences in the reductive behavior were more stark, as the cathodic peak at -0.25 V for α -FeO_x was not detected for α -Fe prior to HER catalysis at *ca.* -0.50 V. The two films could be interconverted: Holding α -FeO_x at -0.68 V for 10 min yields a color change that matches that of α -Fe (grey), while maintaining α -Fe at 1.92 V for 10 min drives a color change towards that of α -FeO_x (brown).

[0066] Evidence for the oxidized and reduced forms of the films being formed under oxygen and nitrogen environments, respectively, is further supported by the different absorption (Fig. 6) and X-ray photoelectron spectroscopy (XPS; Figs. 15 and 16) data. Figure 15 illustrates X-ray photoelectron spectra for α -FeO_x and α -Fe on FTO. The (A) survey scan, and spectral regions corresponding to the (B) iron 2*p* and (C) carbon 1*s* regions, are shown. Figure 16 illustrates X-ray photoelectron spectra detailing the Fe 2*p*_{3/2} region. Sums of the fitting components for (A) α -FeO_x and (B) α -Fe are shown. Curve fitting in A used Gupta Sen parameters based on Fe₂O₃ along with a surface peak and an Fe³⁺ satellite peak. Curve fitting in B used centre-of-gravity peaks for Fe²⁺ and Fe³⁺; a surface peak and a Fe²⁺ satellite peak are also shown. The Fe³⁺ satellite peak is not shown, as it is likely superimposed with the Fe 2*p*_{1/2} peak. The XPS data for α -FeO_x contains a signature iron(III) satellite signal at 719 eV that is not observed for α -Fe, and an iron 2*p*_{3/2} envelope that could be accurately modeled using peak parameters corresponding to Fe₂O₃ (30). The 2*p*_{3/2} envelope of α -Fe was fit to a combination of iron(III), iron(II), and iron(0), where the zero valency was unequivocally implicated by the low-energy shoulder. While these results confirm that α -Fe exists in a more

reduced form, the high susceptibility of the films to areal oxidation prevented confirmation that elemental iron was being formed in exclusivity during the NIRDD process.

[0067] Surrogate films of α -CuO_x and α -Cu prepared by applying the NIRDD process to Cu(eh)₂ on FTO under air and nitrogen were analyzed, respectively, in view of elemental copper oxidizing less readily to Cu₂O and, in turn, CuO (31). XPS data recorded on these samples did indeed yield different spectroscopic signatures (Figs. 4 and 17): The copper 2p_{3/2} envelope for α -CuO_x showed a mixture of CuO and Cu(OH)₂, while the same envelope for α -Cu shows a single peak corresponding to zero- or mono-valent copper sites. Figure 4 illustrates the fitting of the copper 2p_{3/2} region of X-ray photoelectron spectra recorded on thin films of Cu(eh)₂ on FTO after being subjected to the NIRDD process under (A) air and (B) nitrogen, respectively; sum of the fitting components are indicated. Fitting of the data used centre-of-gravity peaks for (A) Cu(O) and Cu(OH)₂, and (B) Cu(I)/Cu(0). Signature copper(II) satellite peaks present in (A) but not (B) confirm a more reduced form of the film when prepared under nitrogen. The computed baselines are indicated. Figure 17 illustrates XPS data for α -CuO_x and α -Cu on FTO. The (A) survey scan, along with the rough fitting of the Cu LMM regions denoting (B) CuO and (C) Cu₂O, are shown.

[0068] Visible inspection of the samples prepared by NIRDD in an inert atmosphere indicated a color consistent with elemental copper (Fig. 18), with XRD measurements ruling out formation of crystalline domains (Fig. 19), lending credence to the samples existing in a reduced form when prepared under nitrogen. Figure 18 illustrates images of solid samples of (A) Cu(eh)₂, (B) Cu(eh)₂ subjected to NIRDD under nitrogen, and (C) Cu(eh)₂ subjected to NIRDD under air. The colors of the samples in (B) and (C) indicate elemental copper and copper oxide, respectively. Figure 19 illustrates powder XRD patterns acquired on as-prepared and annealed ($T_{\text{anneal}} = 500$ °C) α -CuO_x and α -Cu films prepared from Cu(eh)₂ under (A) air and (B) nitrogen. Data recorded on bare FTO substrate is also included. *Inset:* Expanded view highlighting the region where the reflection associated with the crystalline form of CuO at 35.5° is observed. This signal is observed only for the films annealed at 500 °C under air and N₂, *CuO_x-annealed* and *Cu-annealed*.

Example 3 - Novel Synthesis of Mixed-Metal Oxides (MMOx) using IR Irradiation

[0069] Mixed-metal oxides are known to exhibit superior electrocatalytic behavior in basic media, which prompted the synthesis of the binary solid, α -Fe₂Ni₃O_x, by subjecting a mixture of iron precursors [e.g., Fe(eh)₃, FeCl₃ or Fe(NO₃)₃] and nickel precursors [Ni(eh)₂, NiCl₂ or Ni(NO₃)₂] (*mol Fe/mol Ni* 2:3) spin-cast on FTO to the NIRDD process (Fig. 20). Figure 20A illustrates FTIR spectra of Fe₂Ni₃(eh)₃/FTO subjected to NIRDD for the times indicated under air to highlight the progressive loss in intensity of the bands associated with the ligand. In the spectra depicted in Figure 20A, no peaks are present at 32 minutes. The resultant films were amorphous according to powder XRD measurements (Fig. 21A), and the EDX measurements recorded on different regions of the films confirmed uniform metal distributions across the substrates (Figure 32 and Table 2). Figure 21A illustrates powder XRD patterns acquired on as-prepared films of α -Fe₂Ni₃O_x on FTO recorded under air. No reflections were observed other than those associated with FTO. The electrochemical behavior, including OER catalytic activity, also matches films of similar compositions prepared by other methods (Fig. 22A and Table 1), including the absence of an oxidative peak at $E_p \sim 1.45$ V that is present in pure phases of NiO_x. Figure 22A illustrates cyclic voltammograms for thin films of α -Fe₂Ni₃O_x prepared by NIRDD under air. Electrochemistry conditions: Counterelectrode = Pt mesh; reference electrode = Ag/AgCl, KCl (sat'd); scan rate = 10 mV s⁻¹; electrolyte = 0.1 M KOH_(aq); current densities were corrected for uncompensated resistance.

Table 2 – Elemental Analysis of Amorphous Fe₂Ni₃O_x Films Determined by EDX

area	Fig. 32 A		Fig. 32 B	
	% Fe	% Ni	% Fe	% Ni
1	38.86	61.14	38.45	61.55
2	41.35	58.68	40.63	59.37
3	39.32	60.68	39.99	60.01
average (at %)	39.84 ± 1.32	60.16 ± 1.32	39.69 ± 1.12	60.31 ± 1.12
nominal (at %)*	43.34	56.66	43.34	56.66
difference	-3.50	+3.50	-3.65	+3.65

*Based on the relative molar ratios of metal nitrate films deposited on FTO glass; error bars represent the standard deviation between the three different areas of measurement on the surface

Example 4 - Novel Synthesis of Mixed-Metal (MM) using IR Irradiation under Inert Atmosphere

[0070] The binary film, α -Fe₂Ni₃, was prepared in the same manner as α -Fe₂Ni₃O_x, but under nitrogen. Alloy formation was corroborated by the electrocatalytic behavior of the films indicating a more reduced phase compared to that of α -Fe₂Ni₃O_x (Fig. 22B). Figure 20B illustrates FTIR spectra of Fe₂Ni₃(eh)₃/FTO subjected to NIRDD for the times indicated under nitrogen to highlight the progressive loss in intensity of the bands associated with the ligand. The resultant films were amorphous according to powder XRD measurements (Fig. 21B), and the EDX measurements recorded on different regions of the films confirmed uniform metal distributions across the substrates (Figure 32). Figure 21B illustrates powder XRD patterns acquired on as-prepared films of α -Fe₂Ni₃ on FTO recorded under nitrogen. No reflections were observed other than those associated with FTO. Figure 22B illustrates cyclic voltammograms for thin films of (B) α -Fe₂Ni₃ prepared by NIRDD under N₂. Electrochemistry conditions: Counterelectrode = Pt mesh; reference electrode = Ag/AgCl, KCl (sat'd); scan rate = 10 mV s⁻¹; electrolyte = 0.1 M KOH_(aq); current densities were corrected for uncompensated resistance. The alloy, which contains a uniform distribution of metals within the solid (Figure 32 and Table 3), is not a state-of-the-art HER electrocatalyst but is superior to pure phases of α -Fe and α -Ni, thus highlighting that metal cooperativity with other metal combinations may unearth superior catalysts in future studies (7, 17, 32).

Table 3 - Elemental Analysis of Amorphous Fe₂Ni₃ Films Determined by EDX

area	Fig. 32 C		Fig. 32 D	
	% Fe	% Ni	% Fe	% Ni
1	41.55	58.45	39.87	60.13
2	37.95	62.05	40.37	59.61
3	41.88	58.12	37.31	62.69
average (at %)	40.46 ± 2.18	59.54 ± 2.18	39.18 ± 1.65	60.81 ± 1.65

nominal (at %)*	43.34	56.66	43.34	56.66
difference	-2.88	+2.88	-4.15	+4.15

*Based on the relative molar ratios of metal nitrate films deposited on FTO glass; error bars represent the standard deviation between the three different areas of measurement on the surface

Example 5 - *Synthesis of MO_x on Plastic using IR Irradiation*

[0071] The viability of the NIRDD method for situations where the substrate is non-conducting, or sensitive to high temperatures (*e.g.*, interfacial layers in solar cells, carbon-based substrates, *etc.*) was tested. Proof-of-principle experiments of relevance to electrolysis was designed where an 180- μ m thick film of Nafion® was saturated with IrCl₃ or Ir(acac)₃, and subjected to the NIRDD process. The exclusive formation of amorphous IrO_x within the Nafion was found within 60 min of irradiation, with no damage to the membrane, according to electrochemical and FTIR data (Figs. 23 and 24). Figure 23A illustrates cyclic voltammograms for thin films of α -IrO_x/membrane, IrCl₃/membrane, and the membrane, where the membrane is Nafion®. These results show that NIRDD may have the potential to efficiently coat three-dimensional electrodes, which is particularly important in contemporary electrolyzers. Figure 23B illustrates the membrane electrode assembly prepared by mechanically pressing a platinum mesh counter electrode, the prepared Nafion membrane, and a Toray carbon paper gas diffusion layer between two Ti plate electrodes. The catalytic current with the blank membrane is due to the titanium plates mediating the OER reaction. Chronoamperometric measurements were done by holding the potential at 1.8 V for 3600 s. Electrochemistry conditions: counterelectrode = Pt mesh; reference electrode = Ag/AgCl, KCl (sat'd); scan rate = 10 mV s⁻¹; electrolyte = 0.5 M H₂SO_{4(aq)}; current densities were corrected for uncompensated resistance. Figure 24 illustrates (A) full and (B) expanded FTIR spectra of Ir(acac)₃/membrane subjected to NIR radiation for 0 and 60 min. A trace for untreated Nafion membrane is also shown. The magnified spectrum in (B) is included to feature the loss in intensities of the bands associated with the ligand vibrational modes.

Materials

[0072] Iron(III) 2-ethylhexanoate ($\text{Fe}(\text{eh})_3$, 50% w/w in mineral spirits), iridium (III) acetylacetonate ($\text{Ir}(\text{acac})_3$), nickel(II) 2-ethylhexanoate ($\text{Ni}(\text{eh})_2$, 78% w/w in 2-ethylhexanoic acid), manganese(III) 2-ethylhexanoate ($\text{Mn}(\text{eh})_3$, 40% w/w in 2-ethylhexanoic acid), and copper(II) 2-ethylhexanoate ($\text{Cu}(\text{eh})_2$) were purchased from Strem Chemicals. Nafion® N117 proton exchange membranes (177.8 μm thick) were purchased from Ion Power, ferric chloride (98%) anhydrous (FeCl_3) was purchased from Aldrich, iron (III) nitrate nonahydrate ($\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$), nickel nitrate hexahydrate ($\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) and nickel chloride hexahydrate ($\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$) were purchased from Fischer Scientific. All reagents were used without further purification.

Film Syntheses

[0073] **Example 6 - $\alpha\text{-FeO}_x$ on FTO (or glass).** To a 20-mL beaker containing 0.58 g of $\text{Fe}(\text{eh})_3$ (0.60 mmol) was added to 1.07 g hexanes (12.4 mmol). The solutions were then spin-cast onto FTO (or glass) at 3000 rpm for 1 min. The resultant film, $\text{Fe}(\text{eh})_3/\text{FTO}$ (or $\text{Fe}(\text{eh})_3/\text{glass}$), was left under a NIR lamp for 30 min. The following conditions for this “NIRDD” process were used for each experiment unless otherwise stated: the samples were placed underneath a Phillips 175 W NIR lamp, where the bottom of the lamp was positioned 2 cm above the substrate that was set on an aluminum foil surface to help dissipate the heat; the face of the active film was positioned towards the lamp for this process.

[0074] *Alternative methods:* Films were also prepared from FeCl_3 (0.24 g) or $\text{Fe}(\text{NO}_3)_3$ (0.11 g) in deionized water (2 g), that were spin-cast on FTO to form FeCl_3/FTO and $\text{Fe}(\text{NO}_3)_3/\text{FTO}$, respectively, and subject to the NIRDD process described above to form $\alpha\text{-FeO}_x$. Samples prepared on glass were prepared using the same protocol as those prepared on FTO. Figure 29 is an SEM image of FeO_x prepared according to this process.

[0075] **Example 7 - $\alpha\text{-Fe}$ on FTO (or glass).** The films were prepared following the same protocol as $\alpha\text{-FeO}_x$, except the subsequent photolysis step being carried out in an MBraun Labmaster 130 glove box filled with nitrogen.

[0076] **Example 8 - $\alpha\text{-FeO}_x$ -annealed.** Films of $\alpha\text{-FeO}_x$ on FTO were annealed in a furnace at 500 °C for 60 min.

[0077] **Example 9 - α -Fe-annealed.** Films of α -Fe on FTO were annealed for 60 min on a hot plate set at 500 °C inside the glove box. The temperature of the hot plate was confirmed with a Fluke 52 thermocouple.

[0078] **Example 10 - α -IrO_x on FTO (or glass).** To a 20-mL beaker containing 0.09 g of Ir(acac)₃ (0.3 mmol) was added 1.48 g chloroform. The solution was spin-cast onto the substrates (glass or FTO) at 3000 rpm for 1 min. The resultant film, Ir(acac)₃/FTO, was subject to the NIRDD process for 2 h to ensure the reaction was completed. Figure 28 is an SEM image of IrO_x prepared according to this process.

[0079] **Example 11 - α -NiO_x on FTO (or glass).** To a 20-mL beaker containing 0.27 g of Ni(eh)₂ (0.61 mmol) was added to 1.26 g hexanes (14.6 mmol). The solutions were then spin-cast onto the substrates (glass or FTO) at 3000 rpm for 1 min. The resultant film, Ni(eh)₂/FTO, was subject to the NIRDD process until the reaction was complete (~60 min). Figure 26 is an SEM image of NiO_x prepared according to this process.

[0080] *Alternative methods:* Films were also prepared from NiCl₂ (0.17 g) or Ni(NO₃)₂ (0.14 g) in deionized water (2 g), that were spin-cast on FTO to form NiCl₂/FTO and Ni(NO₃)₃/FTO, respectively, and then subject to the NIRDD process to form α -NiO_x on FTO (~30 min).

[0081] **Example 12 - α -MnO_x on FTO (or glass).** To a 20-mL beaker containing 0.55 g of Mn(eh)₃ (0.64 mmol) was added to 1.06 g of hexanes (12.3 mmol). The solutions were then spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, Mn(eh)₃/FTO, was then subject to the NIRDD process to form α -MnO_x on FTO (~30 min).

[0082] **Example 13 - α -CuO_x on FTO (or glass).** To a 20 mL beaker containing 0.21g of Cu(eh)₂ (0.65 mmol) was added to 1.62 g ethanol (35.2 mmol). The solutions were then spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, Cu(eh)₂/FTO, was then subject to the NIRDD process to form α -CuO_x on FTO (~30 min). Figure 31 is an SEM image of CuO_x prepared according to this process

[0083] *Alternative methods:* Films were also prepared from a 0.3 M solution of CuCl_2 in methanol spin-cast on FTO and subject to the NIRDD process as described above to form $\alpha\text{-CuO}_x$.

[0084] **Example 14 - $\alpha\text{-CoO}_x$ on FTO (or glass).** A 0.3 M solution of $\text{Co}(\text{eh})_2$ was prepared in hexanes. The solution was then spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, $\text{Co}(\text{eh})_2/\text{FTO}$, was then subject to the NIRDD process to form $\alpha\text{-CoO}_x$ on FTO (~30 min to 2 h). Figure 27 is an SEM image of CoO_x prepared according to this process.

[0085] *Alternative methods:* Films were also prepared from a 0.3 M solution of CoCl_2 in methanol spin-cast on FTO and subject to the NIRDD process as described above to form $\alpha\text{-CoO}_x$.

[0086] **Example 15 - $\alpha\text{-MoO}_x$ on FTO (or glass).** A 0.3 M solution of $\text{Mo}(\text{eh})_2$ was prepared in hexanes. The solution was then spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, $\text{Mo}(\text{eh})_2/\text{FTO}$, was then subject to the NIRDD process to form $\alpha\text{-MoO}_x$ on FTO (~30 min to 2 h).

[0087] **Example 16 - $\alpha\text{-SnO}_x$ on FTO (or glass).** A 0.3 M solution of $\text{Sn}(\text{eh})_2$ was prepared in methanol. The solution was then spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, $\text{Sn}(\text{eh})_2/\text{FTO}$, was then subject to the NIRDD process to form $\alpha\text{-SnO}_x$ on FTO (~30 min to 2 h).

[0088] **Example 17 - $\alpha\text{-InO}_x$ on FTO (or glass).** A 0.3 M solution of $\text{In}(\text{acac})_3$ was prepared in methanol. The solution was then spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, $\text{In}(\text{acac})_3/\text{FTO}$, was then subject to the NIRDD process to form $\alpha\text{-InO}_x$ on FTO (~30 min to 2 h).

[0089] **Example 18 - $\alpha\text{-RuO}_x$ on FTO (or glass).** A 0.3 M solution of RuCl_3 was prepared in methanol. The solution was then spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, RuCl_3/FTO , was then subject to the NIRDD process to form $\alpha\text{-RuO}_x$ on FTO (~30 min to 2 h). Figure 30 is an SEM image of RuO_x prepared according to this process.

[0090] **Example 19 - α -WO_x on FTO (or glass).** A 0.3 M solution of WCl₆ was prepared in methanol. The solution was then spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, WCl₆/FTO, was then subject to the NIRDD process to form α -WO_x on FTO (~30 min to 2 h).

[0091] **Example 20 - α -Fe₂Ni₃O_x on FTO (or glass).** To a 20-mL beaker containing 0.23 g of Fe(eh)₃ (0.24 mmol) and 0.16 g of Ni(eh)₂ (0.36 mmol) was added 1.28 g of hexanes (14.9 mmol). The mixture was spin-cast onto FTO at 3000 rpm for 1 min. The resultant film, FeNi(eh)/FTO, was then subject to the NIRDD process to form α -Fe₂Ni₃O_x on FTO (~30 min).

[0092] *Alternative methods:* Films were also prepared from a solution of NiCl₂ (0.088 g) [or Ni(NO₃)₂ (0.105 g)] and FeCl₃ (0.039 g) [or Fe(NO₃)₃ (0.097g)] in deionized water (2 g) spin-cast on FTO and subject to the NIRDD process as described above to form α -Fe₂Ni₃O_x.

[0093] **Example 21 - α -Fe₂Ni₃ on FTO (or glass).** Films of α -Fe₂Ni₃ on FTO were prepared in the same fashion as α -Fe₂Ni₃O_x, but the photolysis step was carried out in a glove box.

[0094] **Example 22 - α -IrO_x/membrane.** Nafion membranes were cut into squares with geometric surface areas of 6.25 cm² and then submerged in a bath of 3% w/w H₂O₂ stirring at 800 rpm for ~5 min. The membranes were then left to stand in a bath of stirring 0.5 M H₂SO₄ at 150° C for 60 min. The membranes were dehydrated in a vacuum oven (room temperature, 0.8 atm) for at least 5 h. Excess acid was removed before dehydration with compressed nitrogen. A solution containing 0.016 g of Ir(acac)₃ (0.32 mmol) in 3.2 ml ethanol was then spray-coated on the surface of the dehydrated Nafion to form Ir(acac)₃/membrane. The resultant film was then subjected to the NIRDD process to form α -IrO_x/membrane (~120 min). Similar substrates could be prepared by immersing the Nafion into a 2-mL solution prepared from a bulk solution of 1.0 g of IrCl₃ H₂O (2.8 mmol) in 28 mL H₂O.

Physical Methods

[0095] **Example 23 -** Electrochemical measurements were performed on a C-H Instruments Workstation 660D potentiostat. The Ag/AgCl (sat. KCl) reference electrode (E_{ref}) was

calibrated regularly against a 1-mM aqueous $K_3[Fe(CN)_6]$ solution. Cyclic voltammograms were acquired at a 10 mV s^{-1} scan rate unless otherwise indicated. All potentials were corrected for uncompensated resistance (R_u) and are reported relative to the reversible hydrogen electrode (vs RHE), $E_{RHE} = E + E_{ref} + 0.059(\text{pH}) - iR_u$. Tafel plots were acquired through staircase voltammetry (10 mV steps, 50 s intervals for the final 25 s sampled). For the metal oxide and metal films on FTO, all experiments were carried out using 0.1 M KOH as an electrolyte, unless otherwise noted, in a standard three-compartment electrochemical cell. A Luggin capillary connects the reference and working electrodes while a porous glass frit connects the working electrode to the platinum mesh counter electrode. All experiments involving Nafion were carried out in 0.5 M H_2SO_4 . Membranes were hydrated in 0.2 M H_2SO_4 prior to electrochemical experiments. Measurements were performed in a customized three-electrode test cell using the above Ag/AgCl reference electrode. All potentials were corrected for R_u . The membrane electrode assembly (MEA) was prepared by mechanically pressing a platinum mesh counter electrode (Aldrich), the prepared Nafion membrane, and a Toray carbon paper gas diffusion layer (Ion Power) between two Ti plate electrodes (McMaster Carr). No aggregation was induced on the test cell besides that from evolved gaseous products. Powder X-ray diffraction (XRD) data was recorded with a Bruker D8 Advance diffractometer using Cu $K\alpha$ radiation. Data was collected between 2θ angles of 5° and 90° with a step size of 0.04° . The step time was 0.6 s unless otherwise indicated. Thermogravimetric Analysis and Differential Scanning Calorimetry (TGA/DSC) measurements were collected simultaneously with a PerkinElmer Simultaneous Thermal Analyzer (STA) 6000. These measurements were carried out under both air and N_2 at a 20 mL min^{-1} flow rate. Starting from a temperature of 50°C , the temperature was ramped up ($10^\circ\text{C min}^{-1}$) until 100°C where it was held for one minute. It was then ramped at $10^\circ\text{C min}^{-1}$ until a final temperature of 500°C was reached and held for an additional minute. For constant temperature measurements, the temperature was ramped up ($10^\circ\text{C min}^{-1}$) until 200°C where it was held for 60 minutes. UV-vis absorption spectroscopy on fresh and on metal oxide films was performed using a Perkin Elmer Lambda 35 UV-vis spectrometer with a solid sample holder accessory. Baseline scans were performed with clean glass. X-ray photoelectron spectroscopy (XPS) measurements were collected on a Leybold MAX200 spectrometer using Al K-alpha radiation. The pass energy used for the survey scan was 192 eV while for the narrow scan it was 48 eV. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) measurements were carried out on a FEI Helios NanoLab 650 dual beam scanning electron microscope with an EDAX Pegasus system with

EDS detector. The magnification was set to 2000X, the accelerating voltage was set to 2.0 KeV, the current was set to 51 nA and the working distance was 9 mm.

[0096] Example 24 - The temperature of the substrates was tracked with a Fluke 52 thermocouple attached to a multimeter. For the FTO measurements, constant contact of the tip of the detector was maintained throughout the experiment. For the thermocouple measurements, the tip of the detector was dipped in Fe(eh)₃. The substrate & thermocouple was placed 2 cm from the lamp. Temperature values were recorded every 5 min.

[0097] Example 25 – All amorphous film examples could also be fabricated on different substrates including fluorine doped tin oxide (FTO), glass, copper, titanium, nafion membrane, plastic and glassy carbon using the same protocols as described in the examples above.

[0098] It will be understood by those of skill in the art that the scope of the claims should not be limited by the preferred embodiments set forth in the examples, but should be given the broadest interpretation consistent with the description as a whole.

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We claim:

1. A process for forming an amorphous metal-containing electrocatalytic film, the process comprising the steps of:
 - a) providing a substrate;
 - b) coating the substrate with a metal precursor solution; and
 - c) exposing the coated substrate to near-infrared radiation to form the amorphous metal-containing film.
2. The process according to claim 1, wherein the amorphous metal-containing film is an amorphous metal oxide, an amorphous mixed metal oxide, an amorphous metal, or an amorphous mixed metal.
3. The process according to claim 1 or 2, wherein the amorphous metal-containing film comprises a metal selected from iron, iridium, manganese, nickel, copper, ruthenium, cobalt, tungsten, indium, tin, molybdenum, or any combination thereof.
4. The process according to claim 1, wherein the metal precursor is a metal salt.
5. The process according to claim 4, wherein the metal salt is MCl_x or $M(NO_3)_x$, where x is 2 or 3.
6. The process according to claim 4, wherein the metal salt is selected from the group consisting of $FeCl_3$, $Fe(NO_3)_3$, $IrCl_3$, $NiCl_2$, $Ni(NO_3)_2$, Fe_2Ni_3Cl , $CoCl_2$, $RuCl_3$, $CuCl_2$, and WCl_6 .
7. The process according to claim 1, wherein the metal precursor is a metal coordination complex.
8. The process according to claim 7, wherein the metal coordination complex is a 2-ethylhexanoate derivative or an acetylacetonate derivative.

9. The process according to claim 7, wherein the metal coordination complex is selected from the group consisting of $\text{Fe}(\text{eh})_3$, $\text{Cu}(\text{eh})_2$, $\text{Ir}(\text{acac})_3$, $\text{Ni}(\text{eh})_2$, $\text{Mn}(\text{eh})_3$, $\text{Co}(\text{eh})_2$, $\text{Mo}(\text{eh})_2$, $\text{Sn}(\text{eh})_2$, $\text{In}(\text{acac})_3$, and $\text{Fe}_2\text{Ni}_3(\text{eh})_3$.
10. The process according to any one of claims 1 to 9, wherein the substrate is glass, fluorine-doped tin oxide-coated glass, Nafion ®, a metallic substrate, plastic, glassy carbon or stainless steel.
11. The process according to any one of claims 1 to 10, wherein the step of exposing the coated substrate to near-infrared radiation is conducted in an oxidizing atmosphere.
12. The process according to claim 11, wherein the amorphous metal-containing film comprises $\alpha\text{-FeO}_x$, $\alpha\text{-IrO}_x$, $\alpha\text{-NiO}_x$, $\alpha\text{-MnO}_x$, $\alpha\text{-Fe}_2\text{Ni}_3\text{O}_x$, $\alpha\text{-CuO}_x$, $\alpha\text{-CoO}_x$, $\alpha\text{-MoO}_x$, $\alpha\text{-SnO}_x$, $\alpha\text{-InO}_x$, $\alpha\text{-RuO}_x$, or $\alpha\text{-WO}_x$,
13. The process according to any one of claims 1 to 10, wherein the step of exposing the coated substrate to near-infrared radiation is conducted in an inert atmosphere.
14. The process according to claim 13, wherein the amorphous metal-containing film comprises $\alpha\text{-Fe}$, $\alpha\text{-Cu}$, $\alpha\text{-Fe}_2\text{Ni}_3$, $\alpha\text{-Ni}$, or $\alpha\text{-Mn}$.
15. The process according to any one of claims 1 to 14, further comprising the step of tuning the properties of the electrocatalyst.
16. The process according to claim 15, wherein the tuning step comprises annealing the metal oxide film.
17. An electrocatalytic material formed by the process defined by any one of claims 1 to 16.

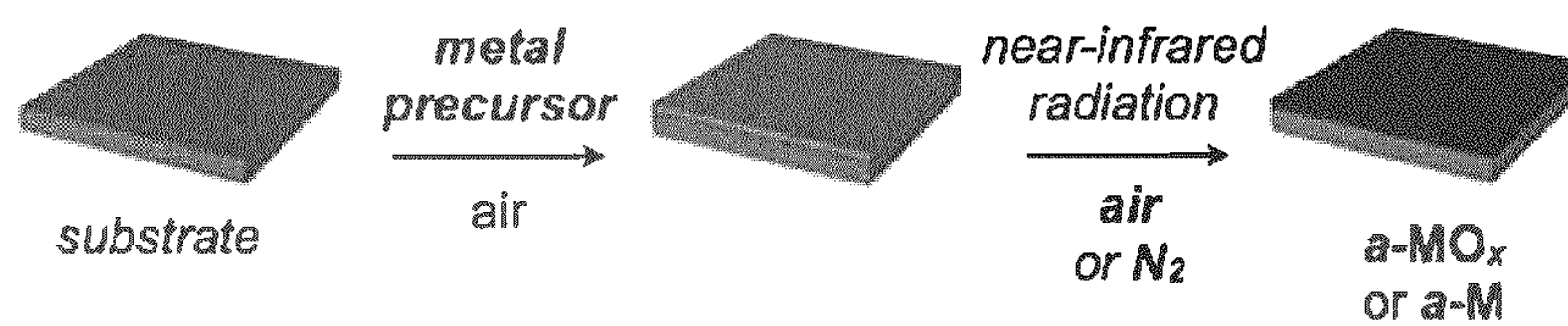


Fig. 1

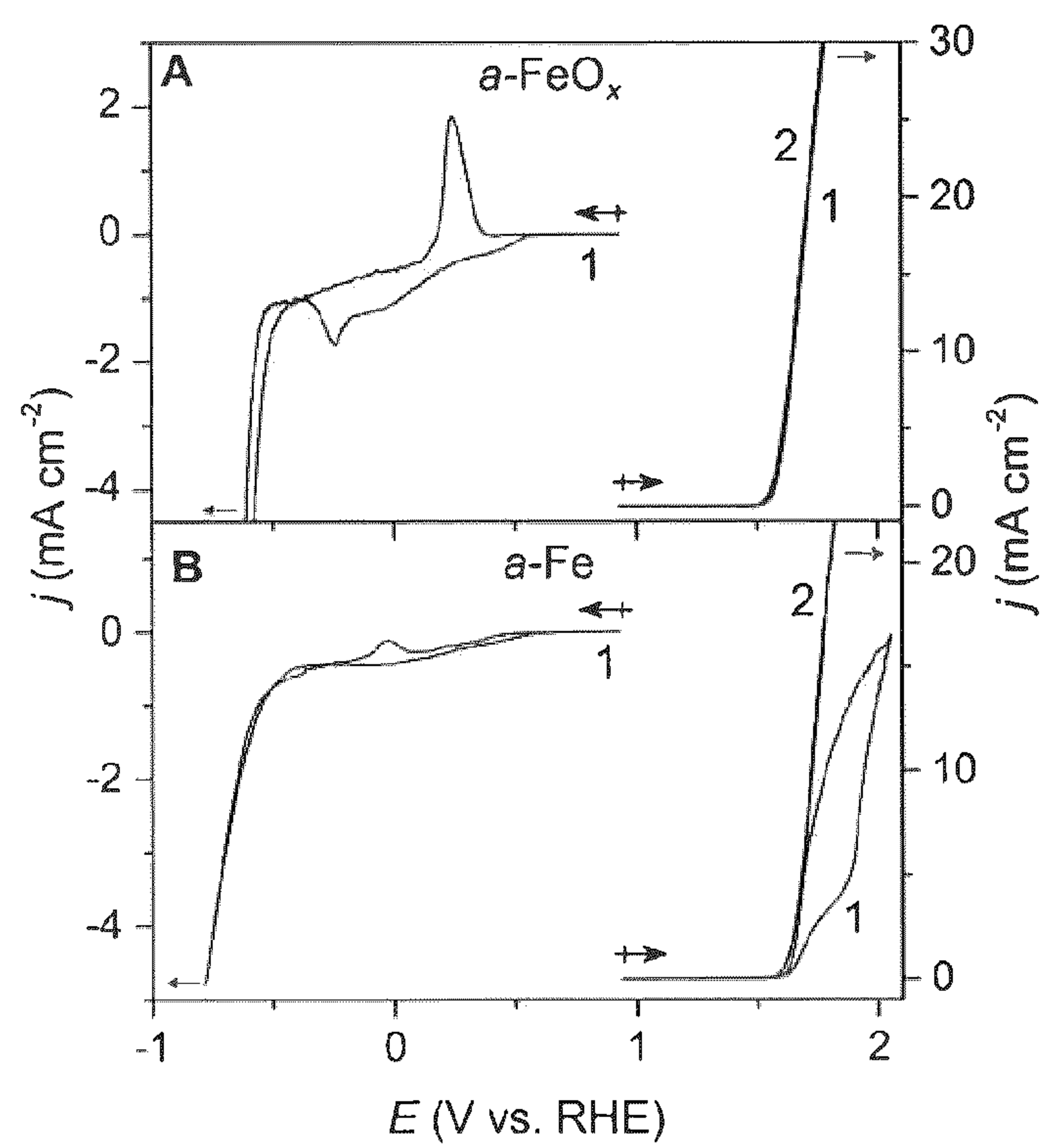


Fig. 2

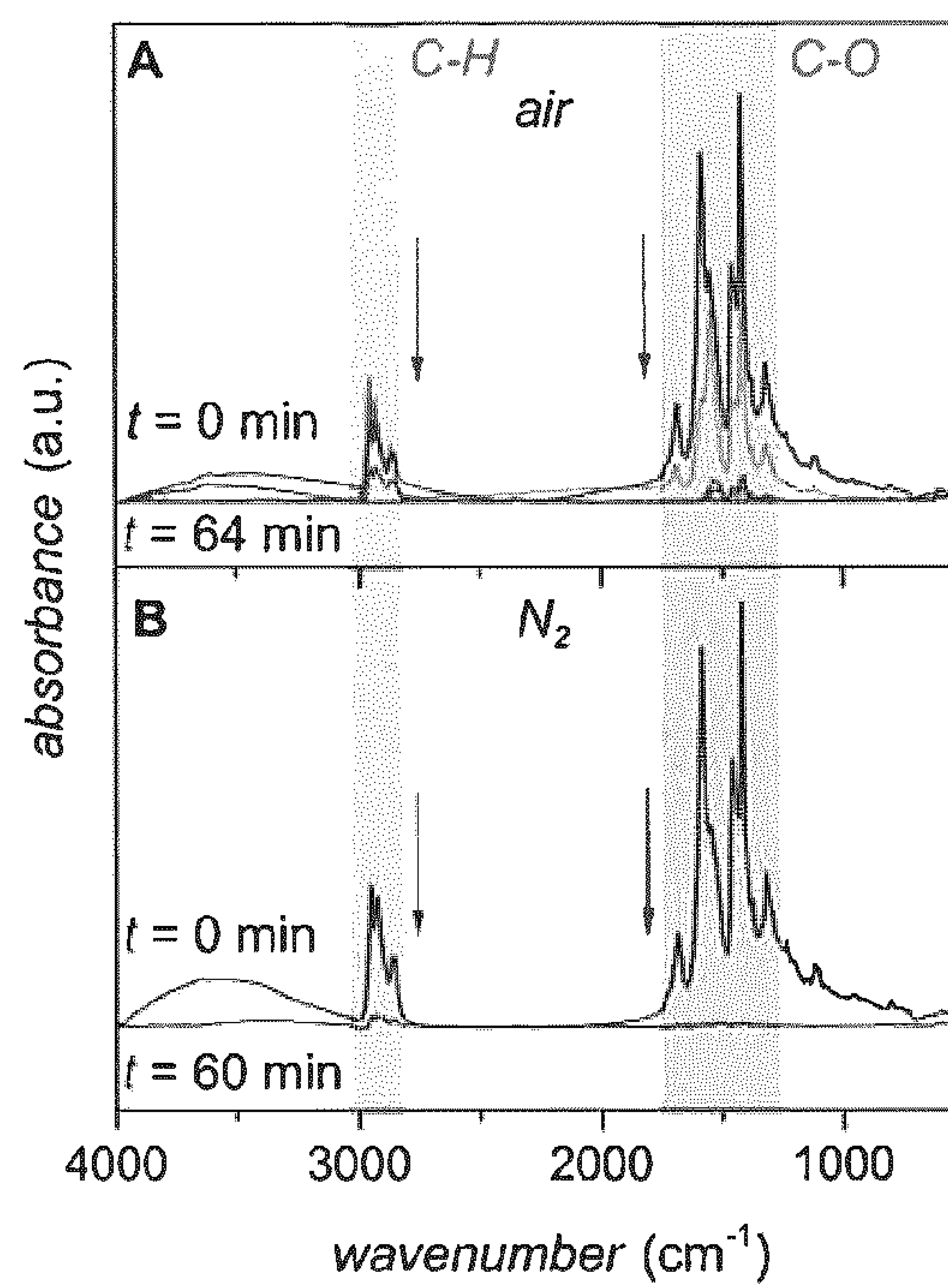


Fig. 3

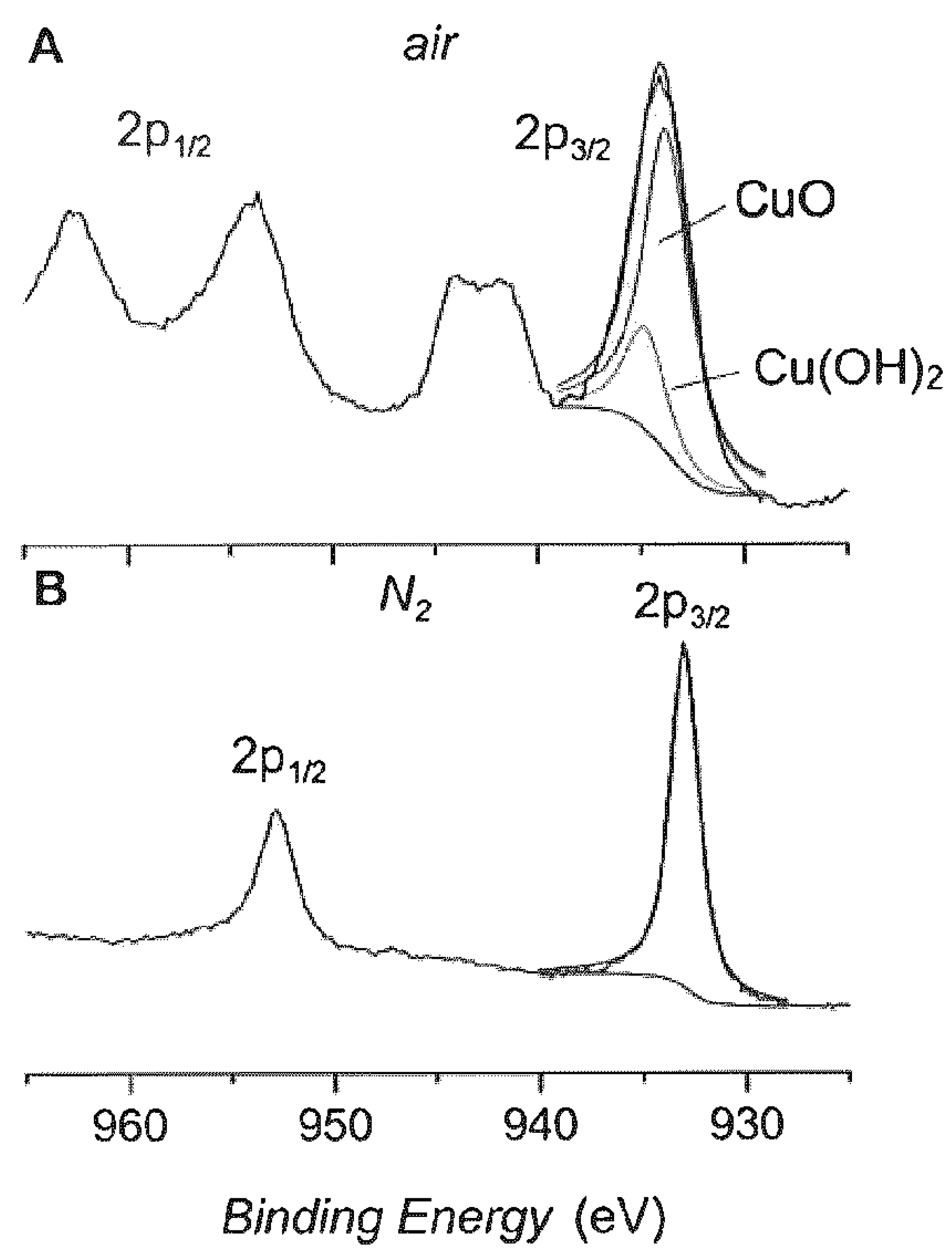


Fig. 4

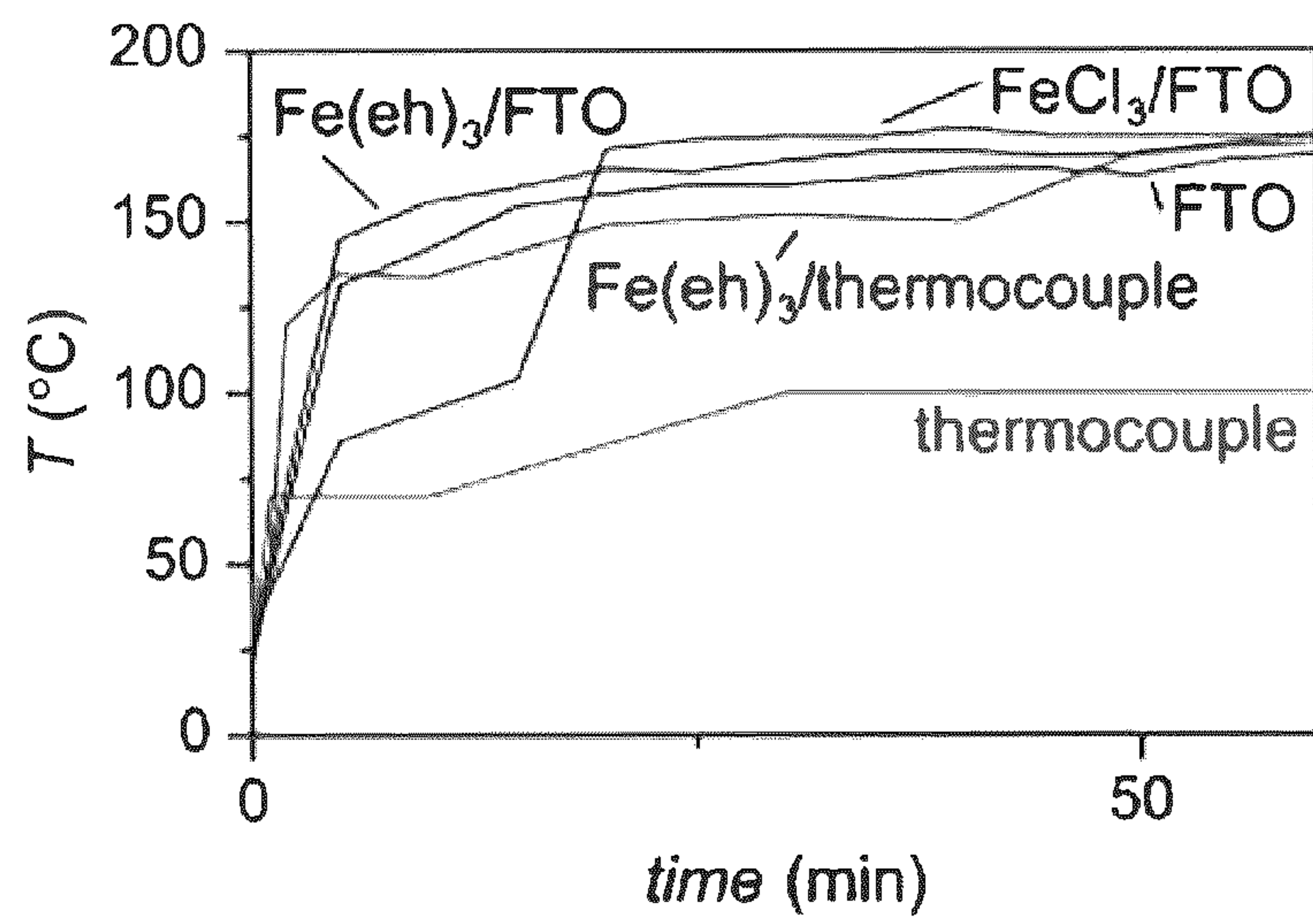


Fig. 5

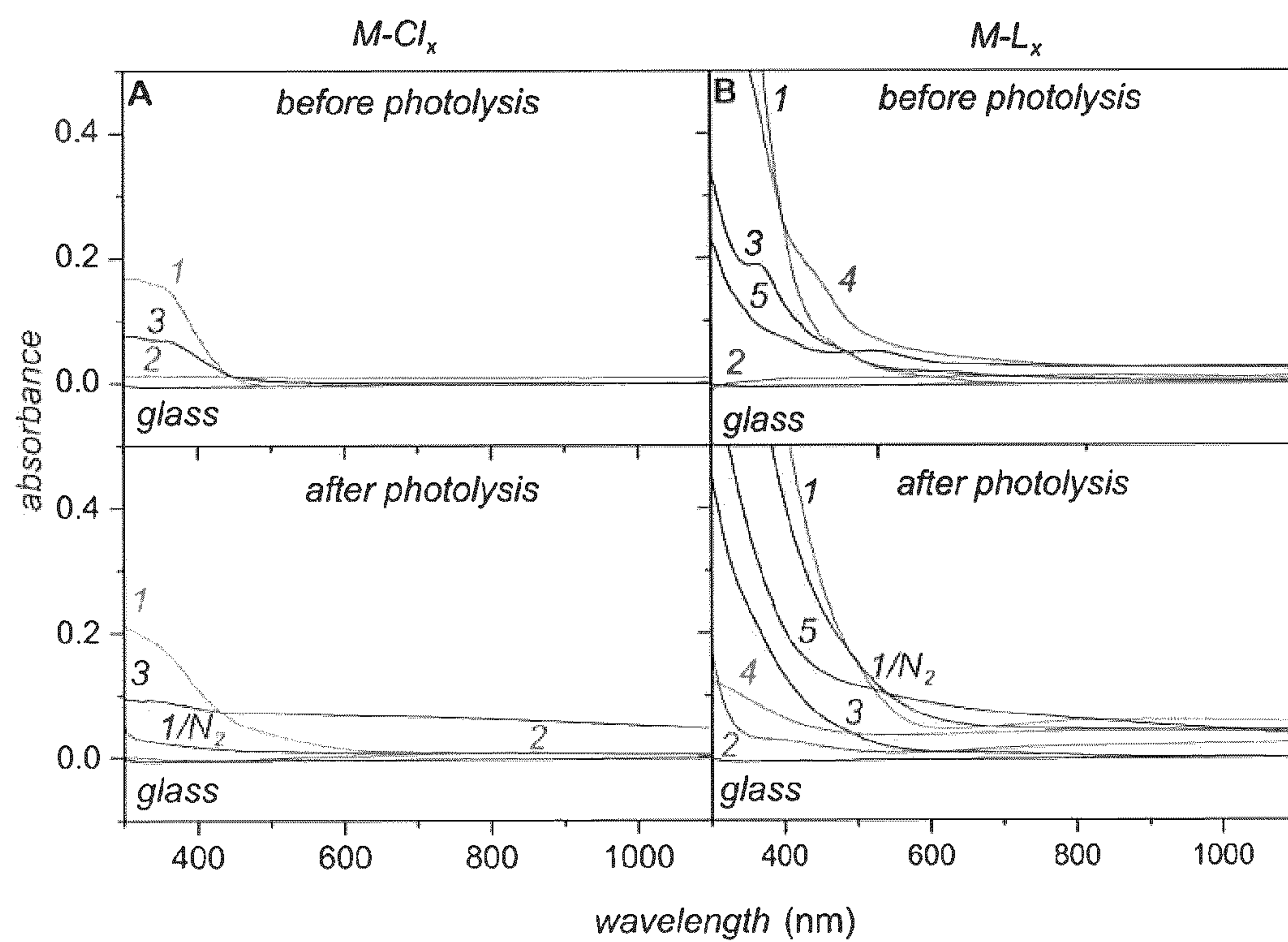


Fig. 6

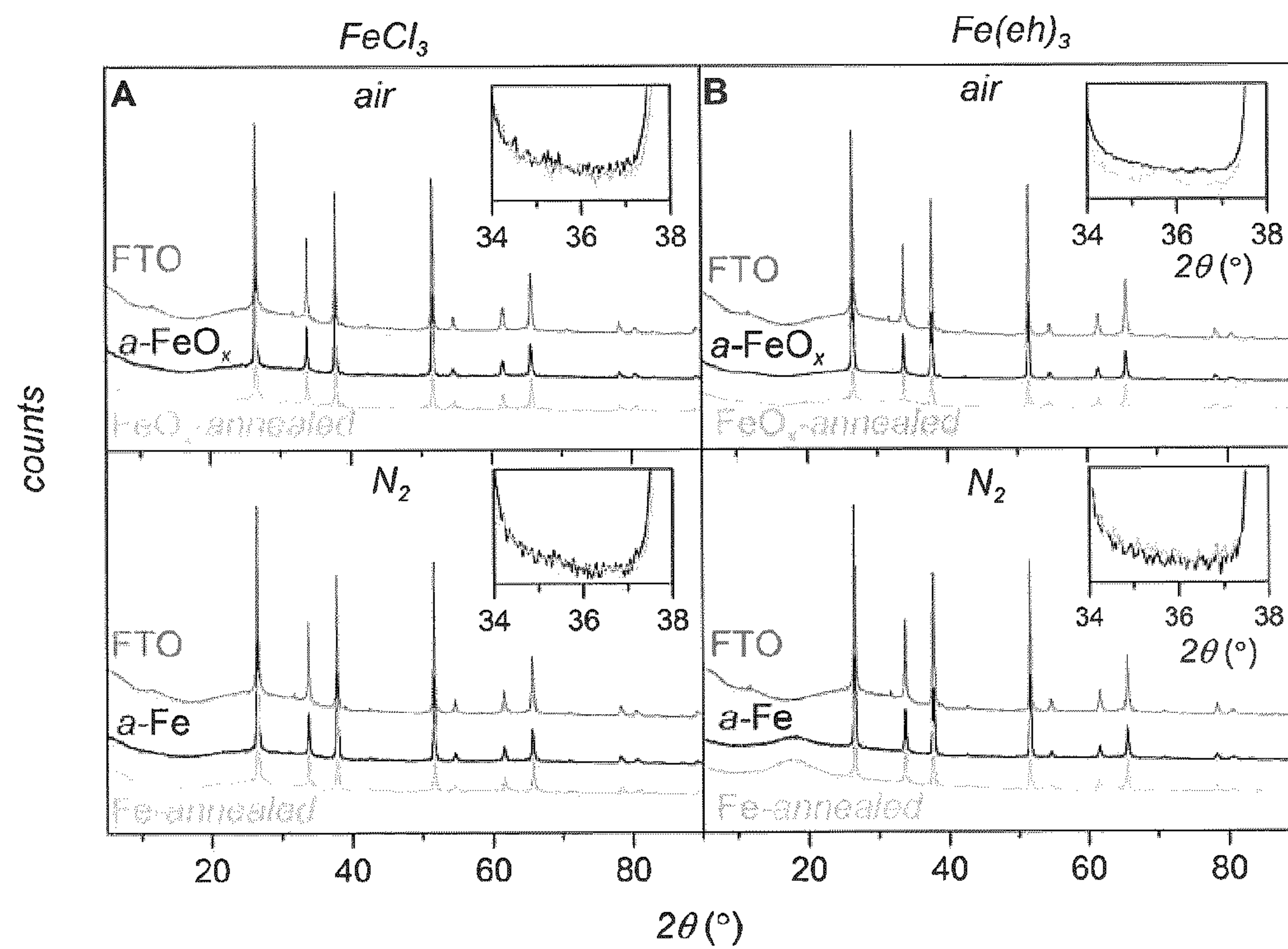


Fig. 7

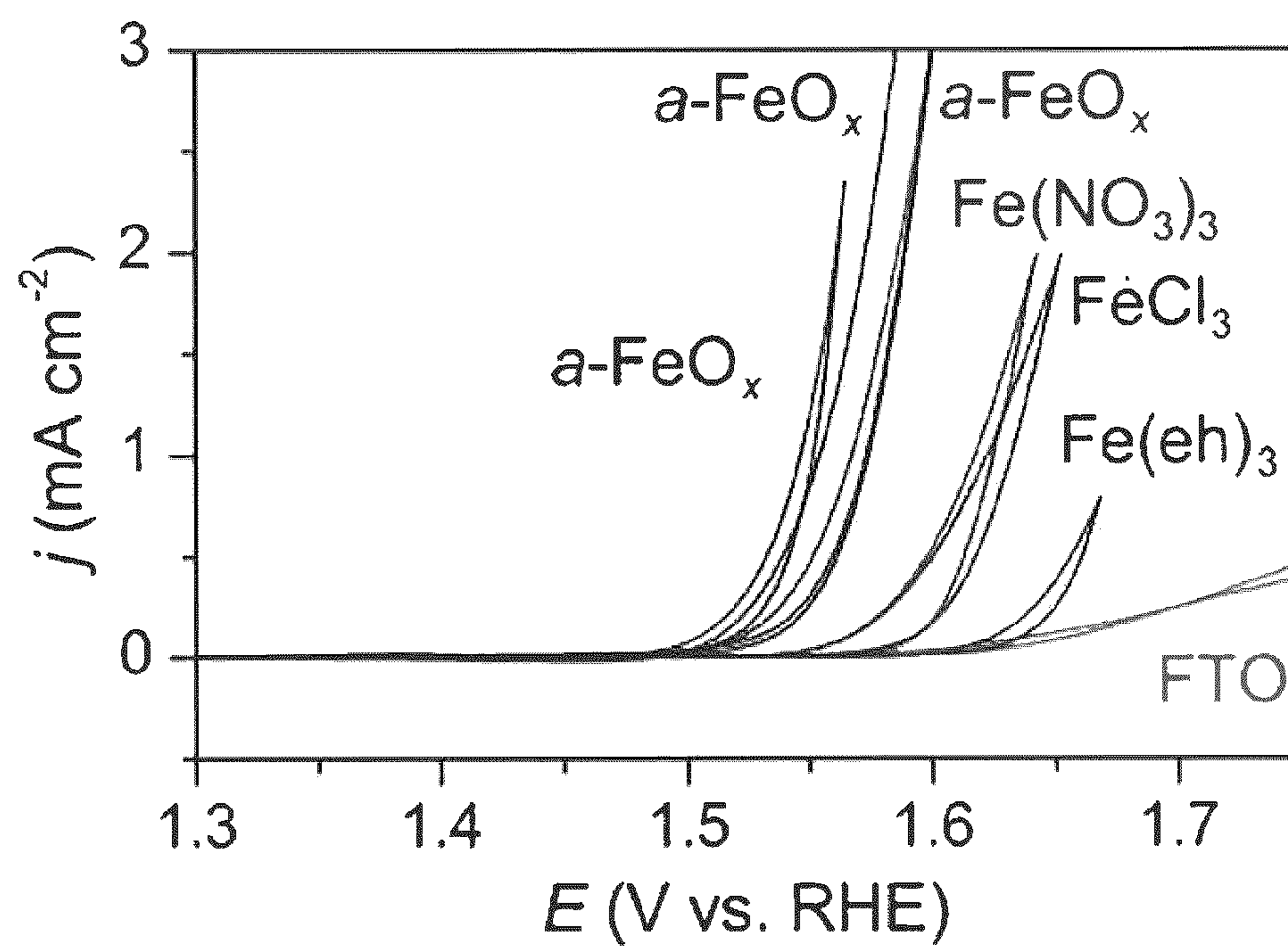


Fig. 8

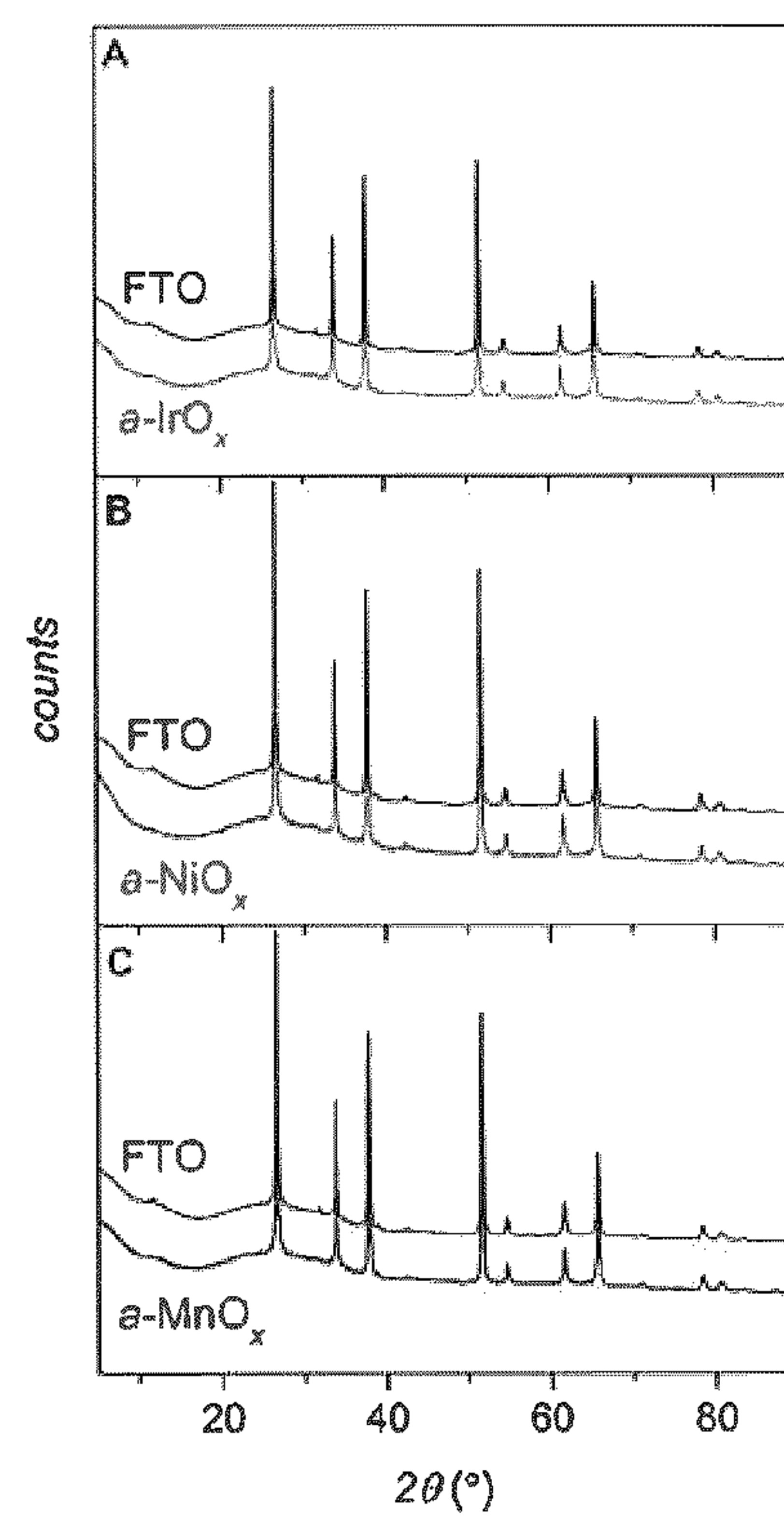


Fig. 9

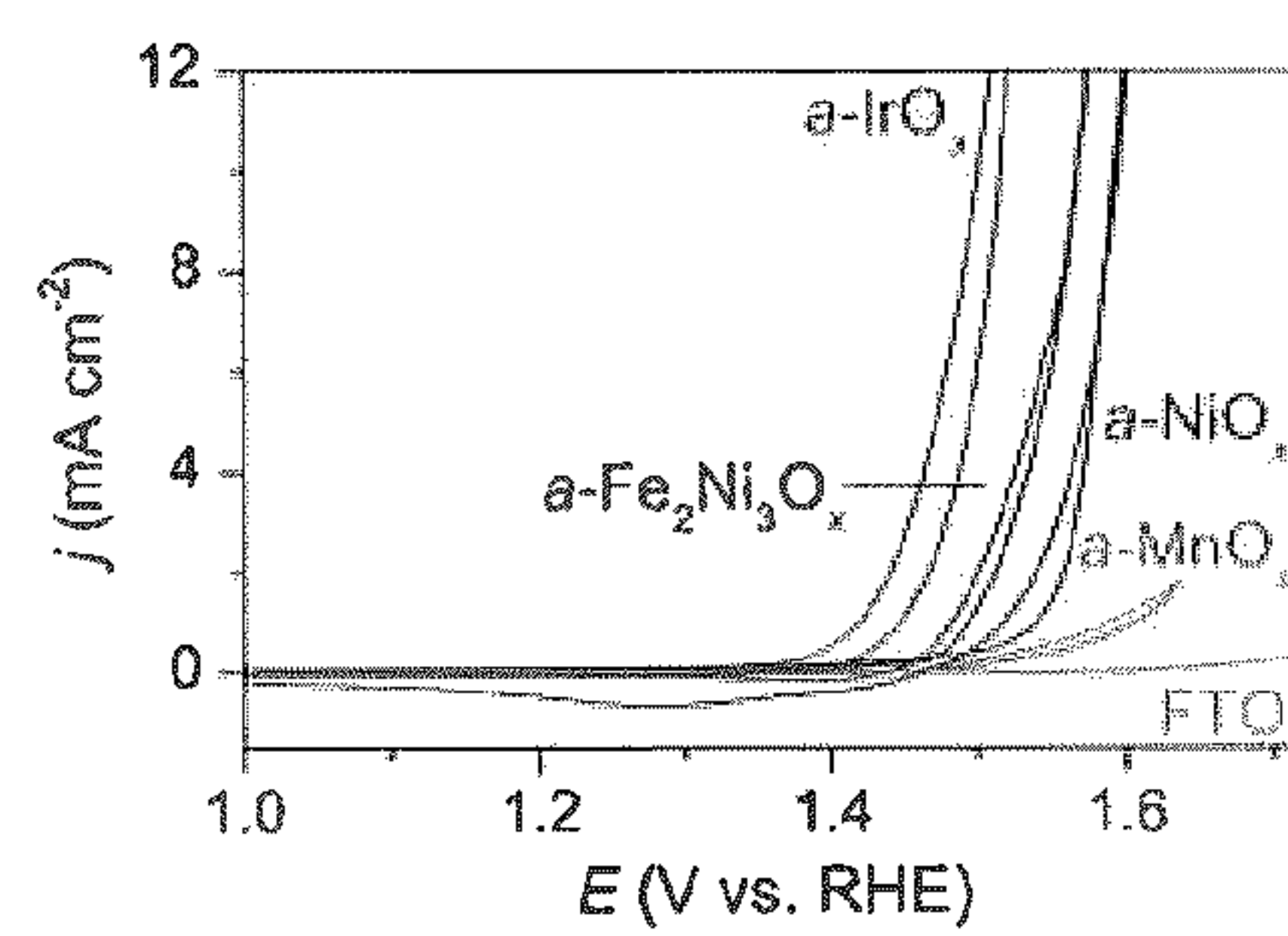


Fig. 10

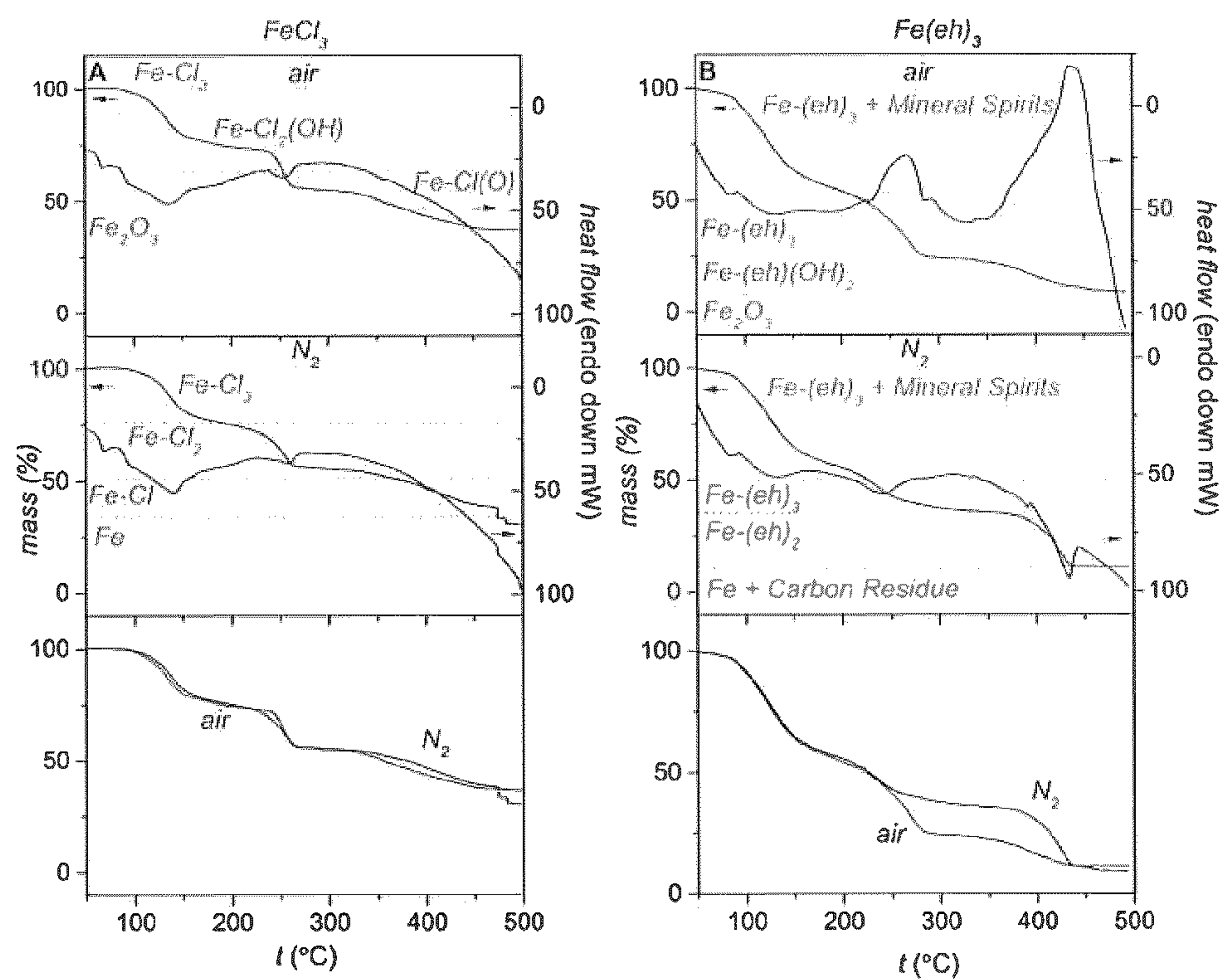


Fig. 11

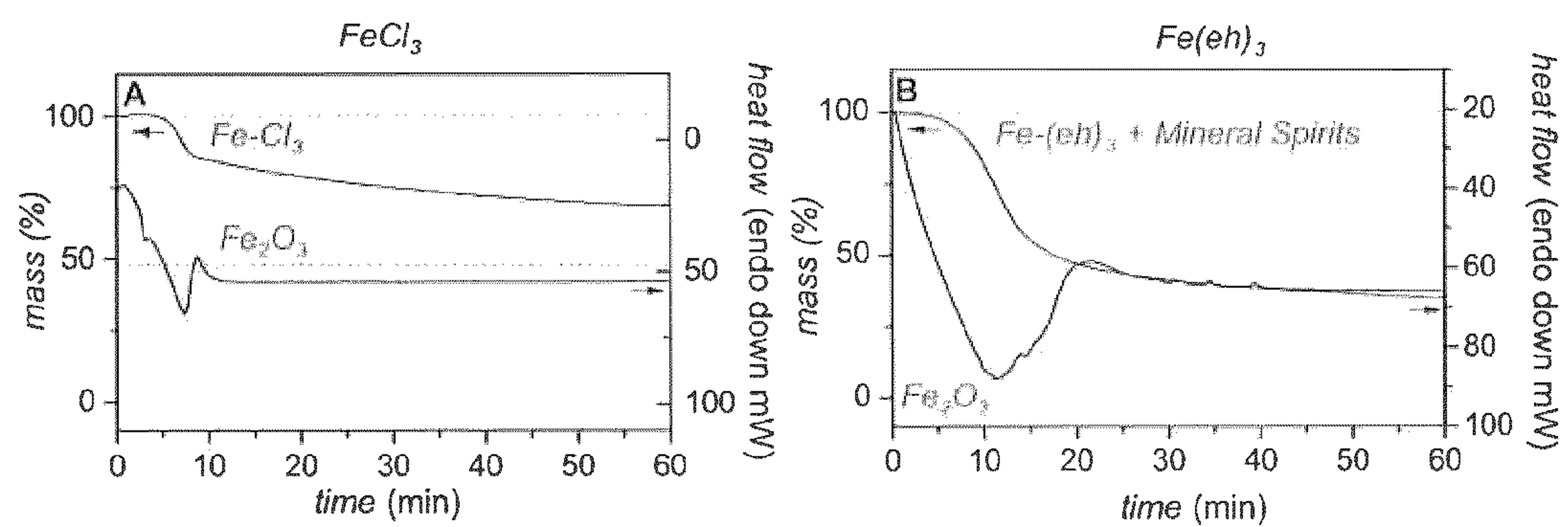


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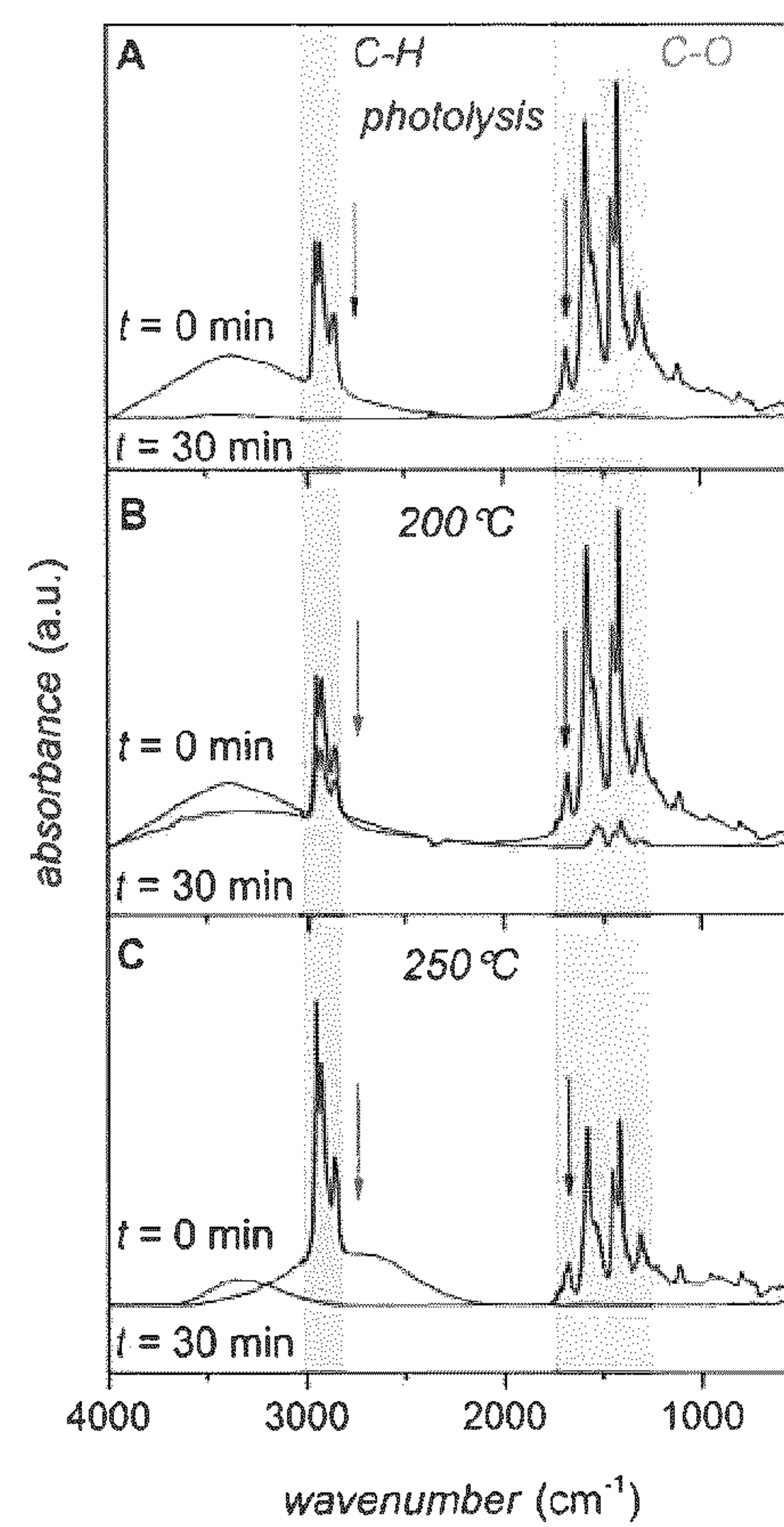


Fig. 13

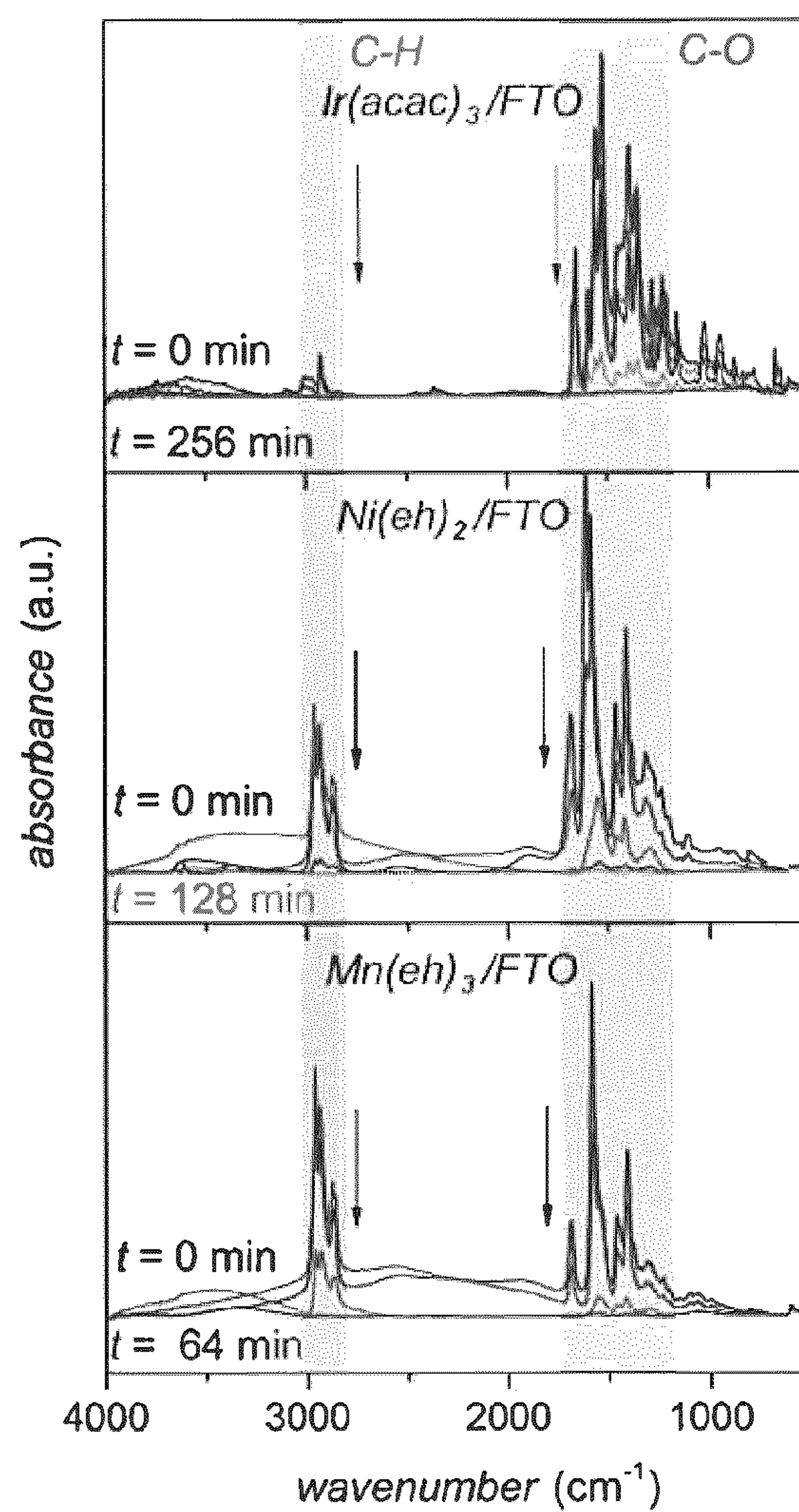


Fig. 14

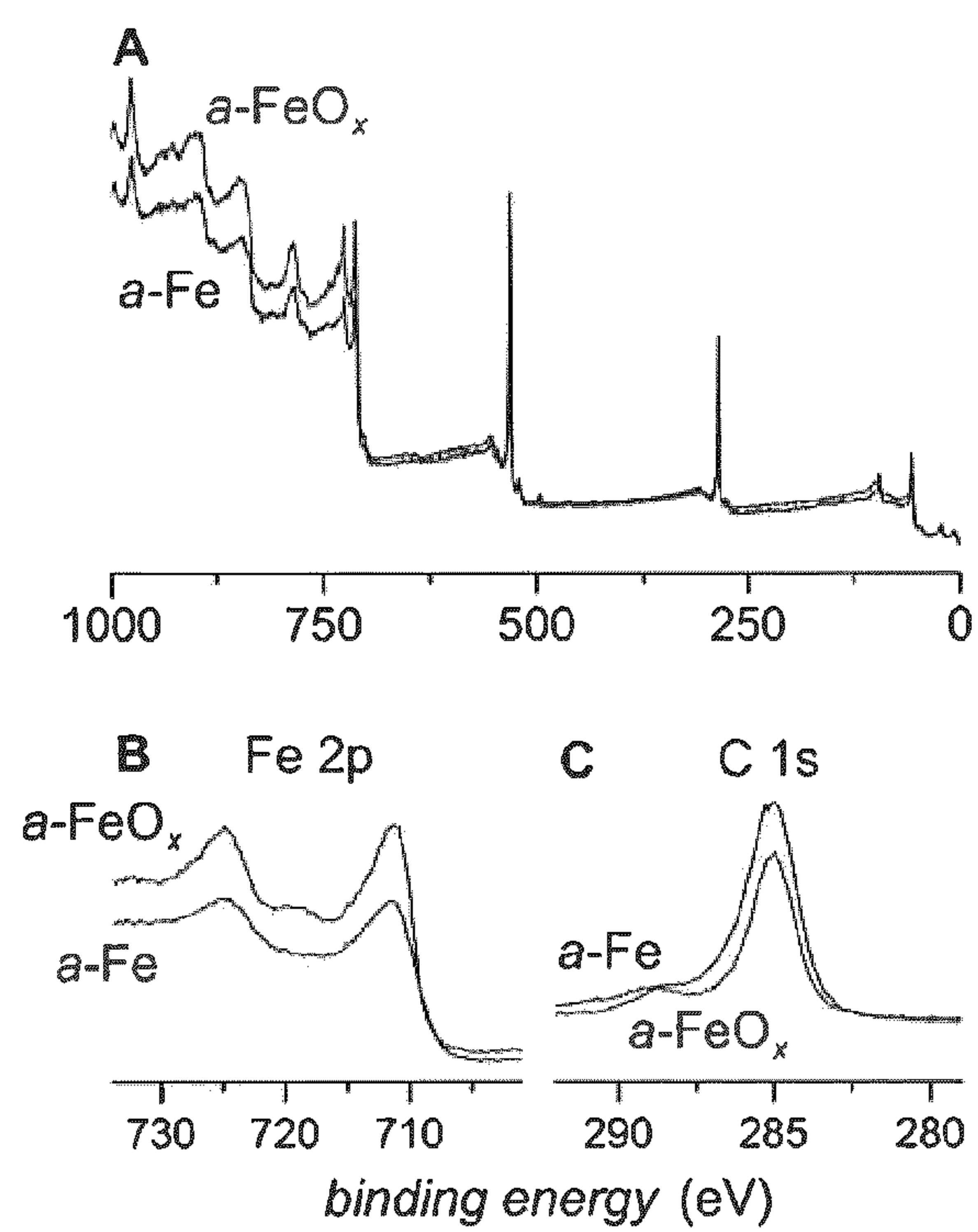


Fig. 15

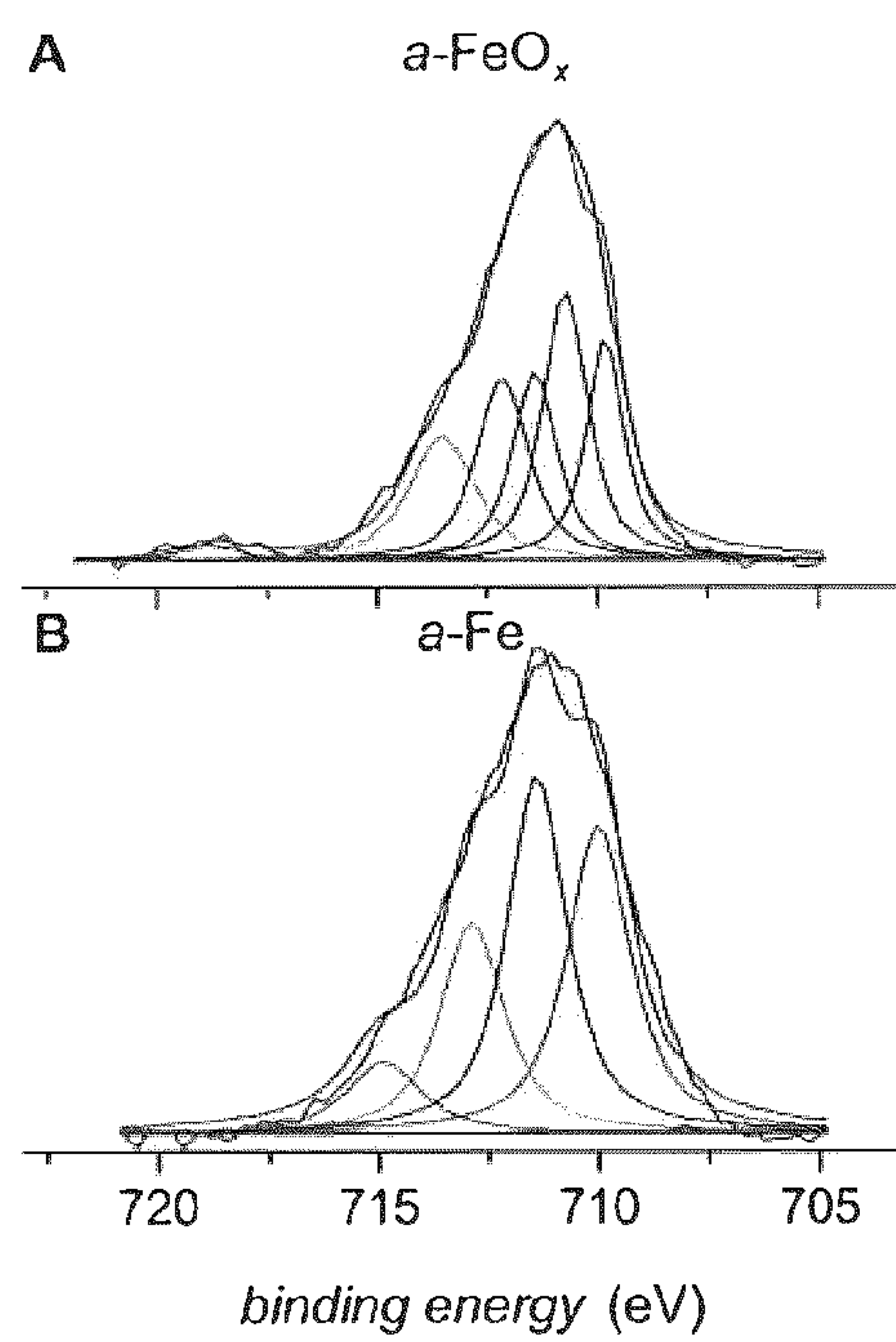


Fig. 16

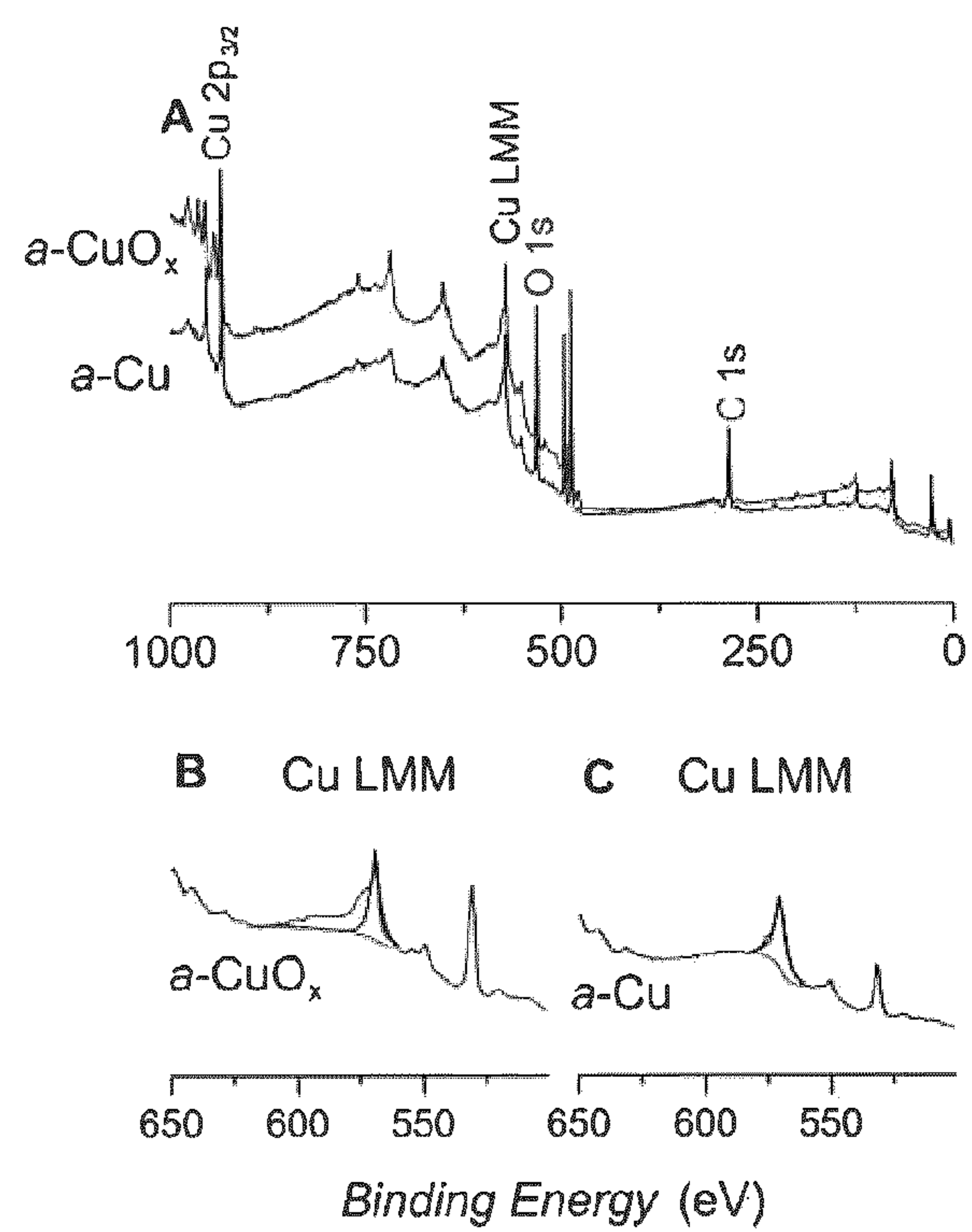


Fig. 17

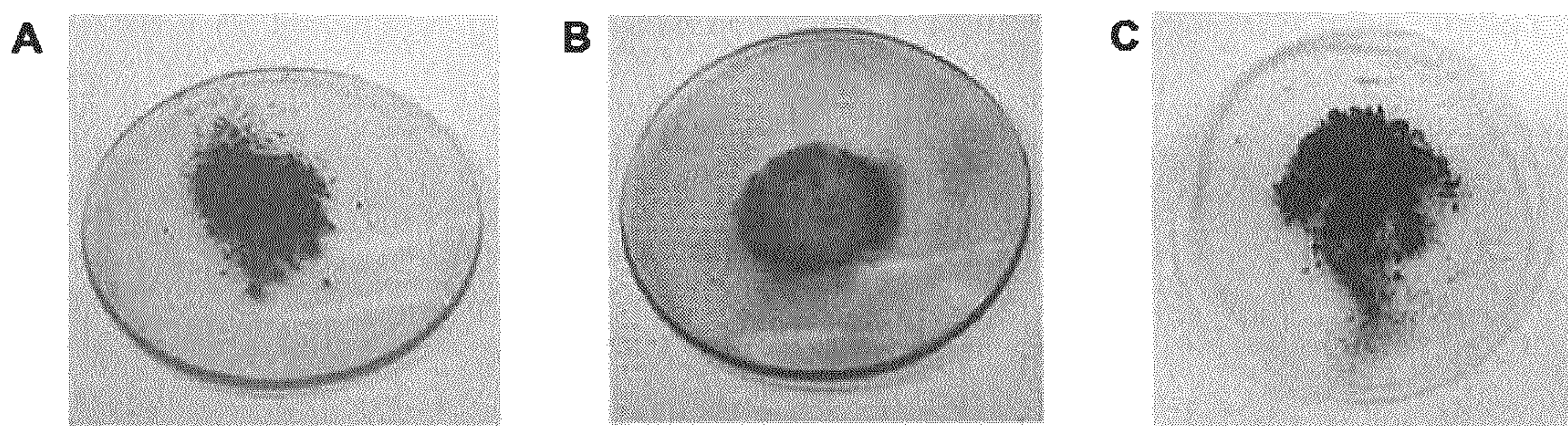


Fig. 18

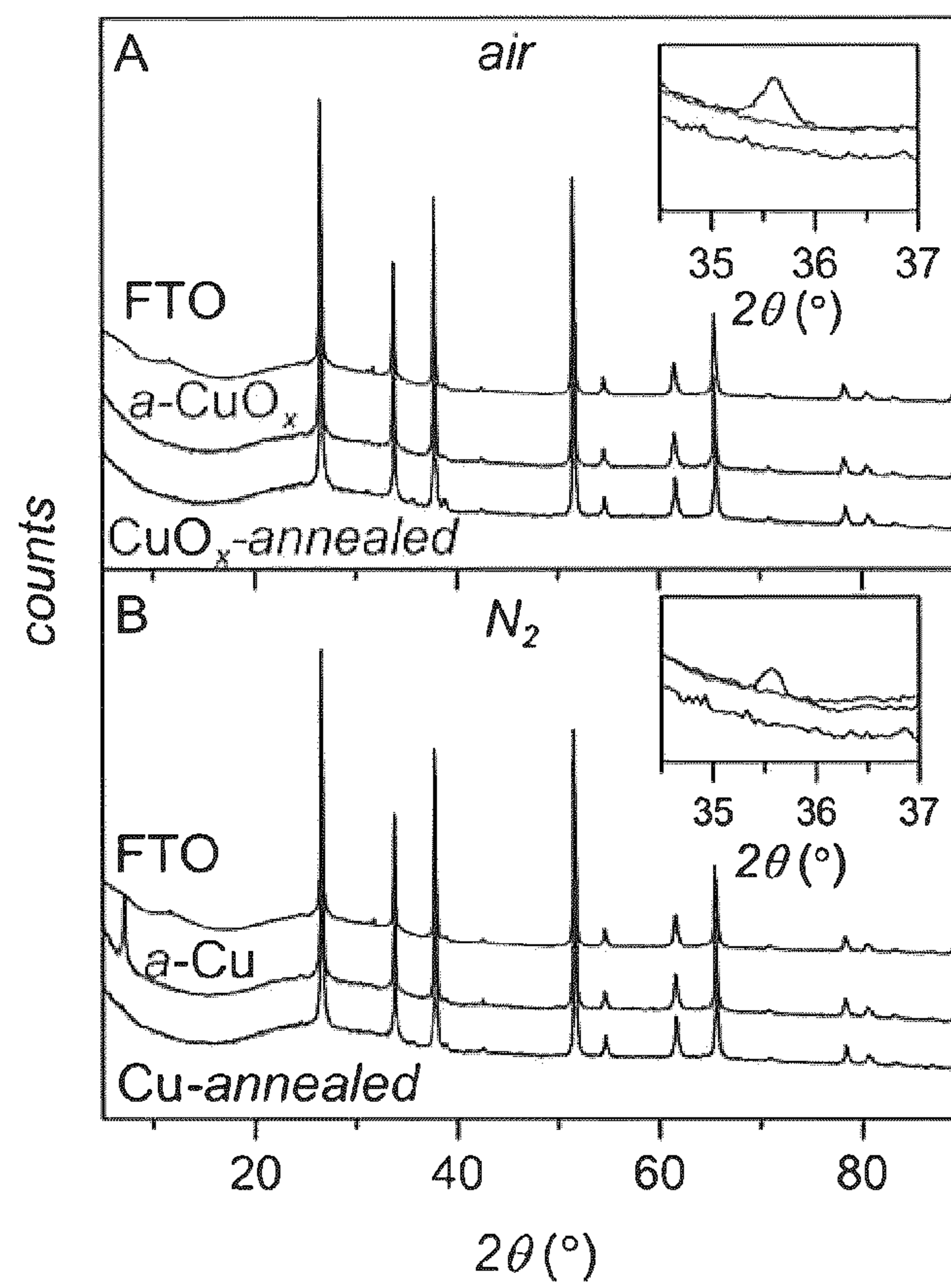


Fig. 19

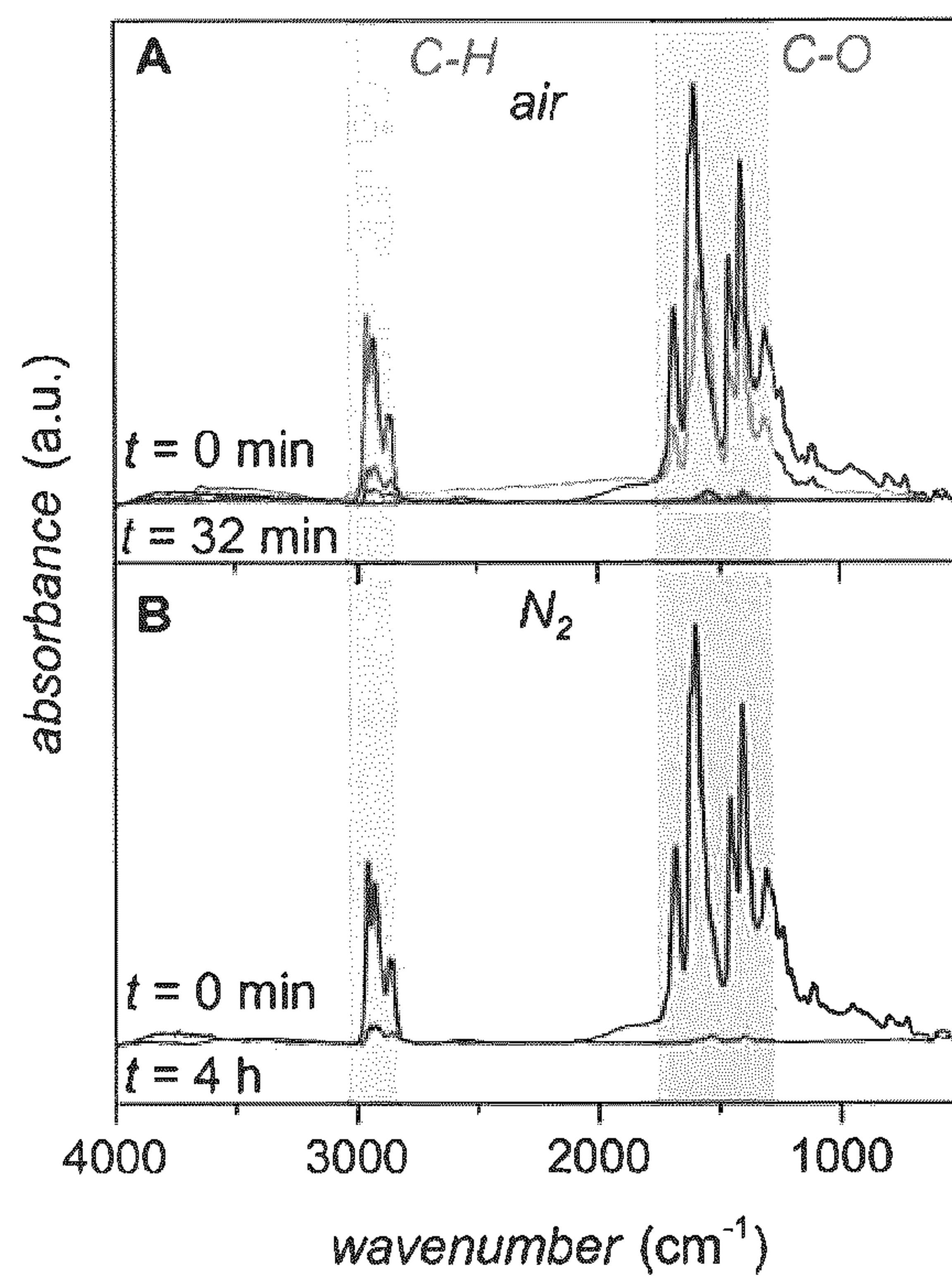


Fig. 20

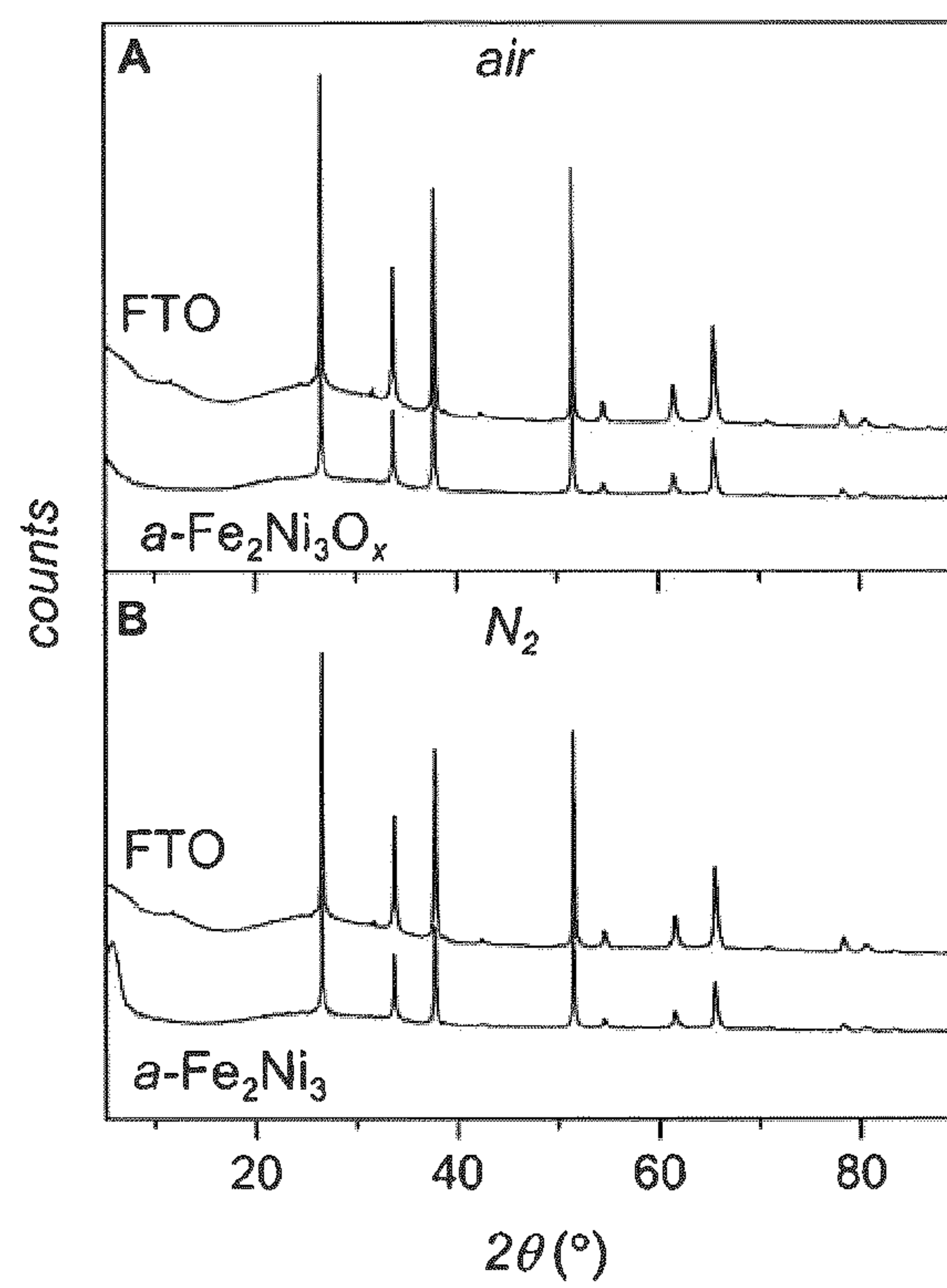


Fig. 21

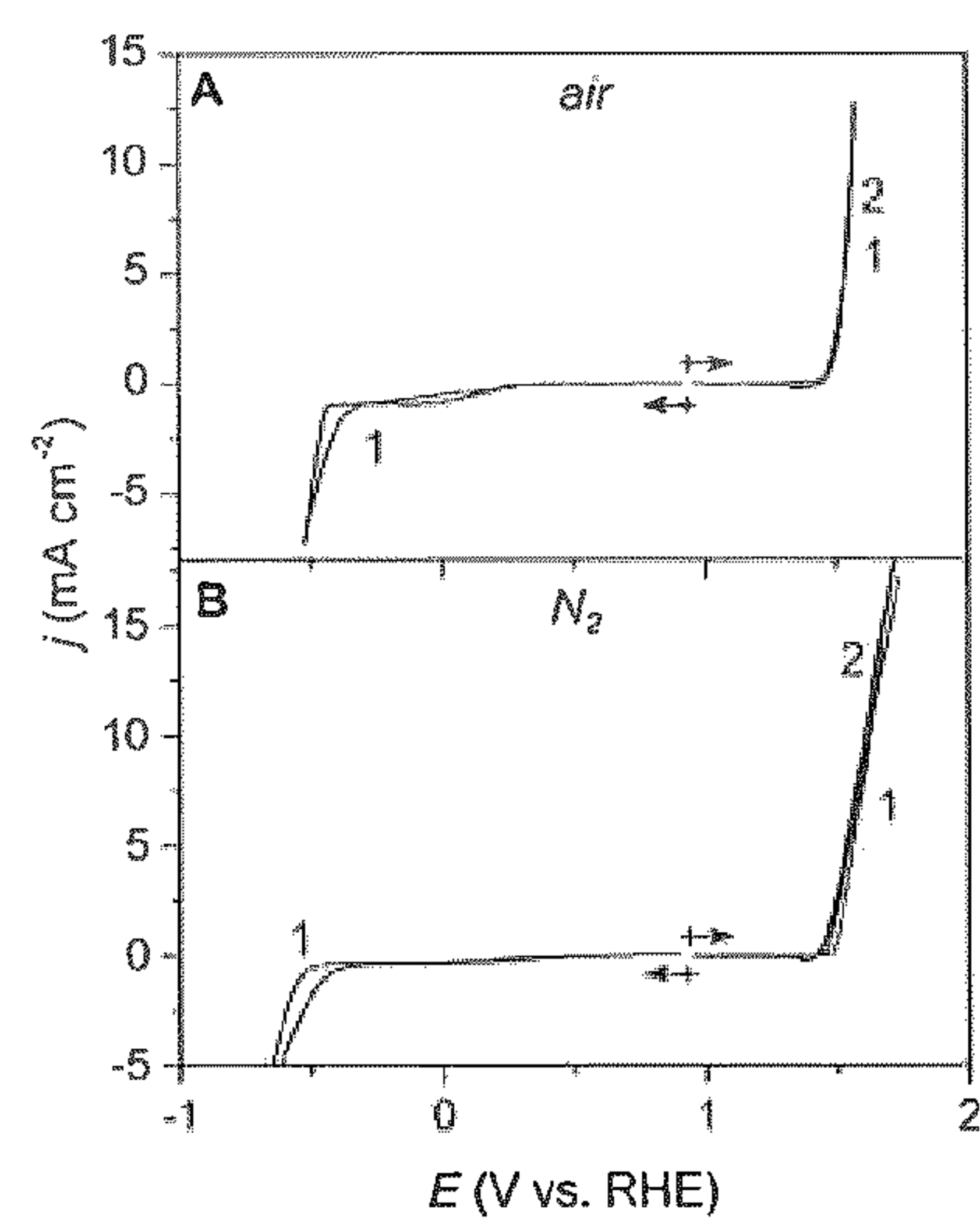


Fig. 22

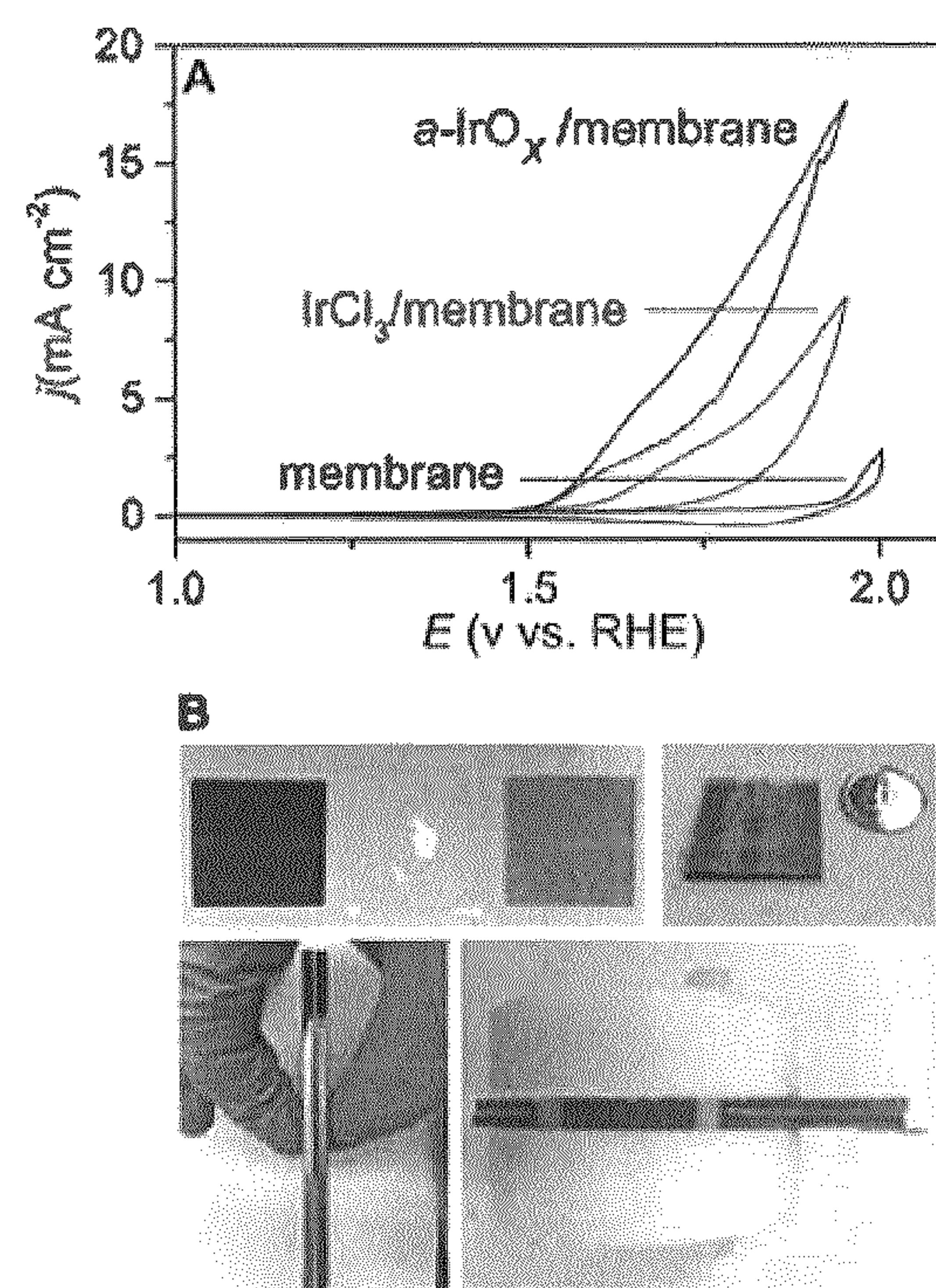


Fig. 23

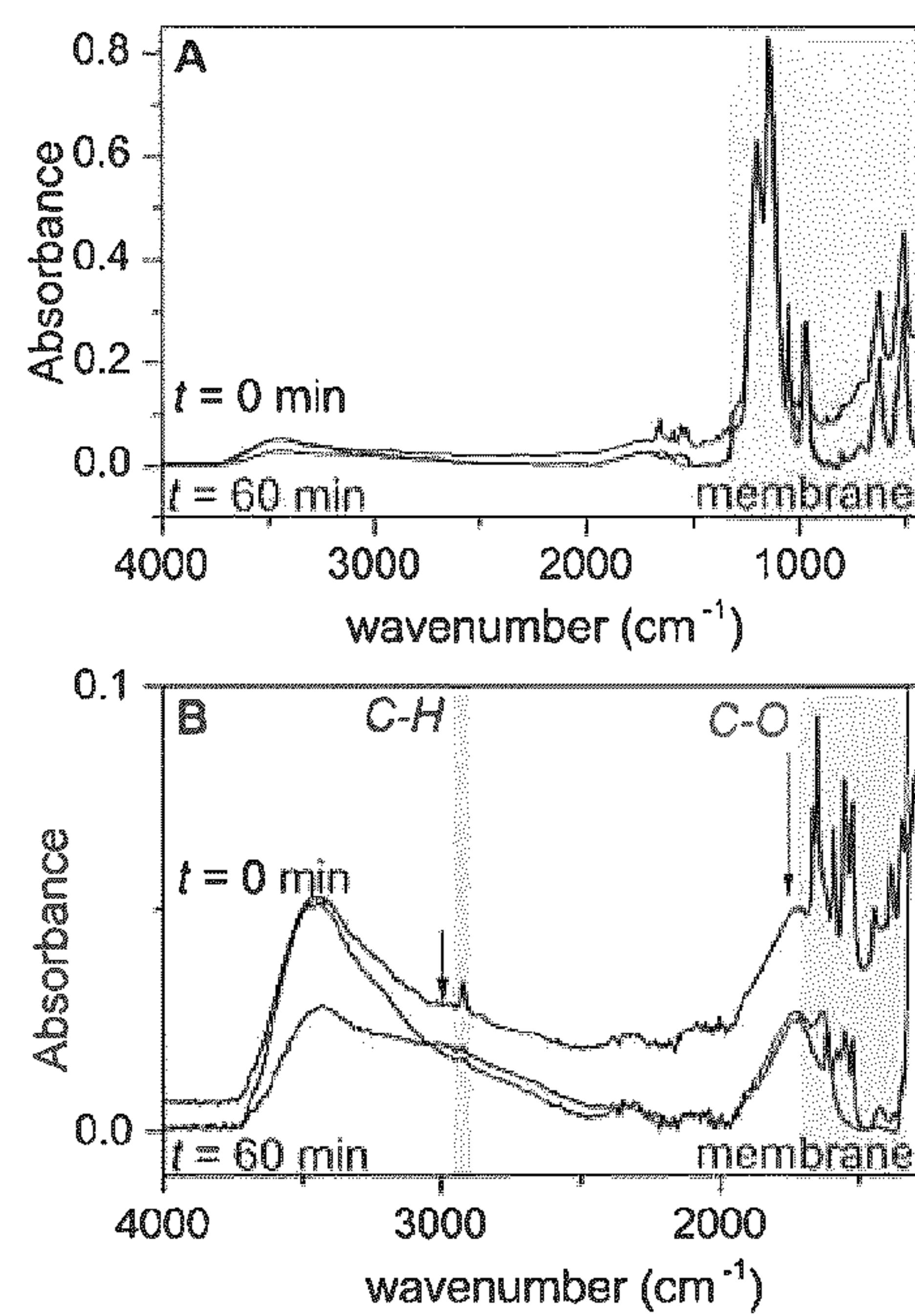


Fig. 24

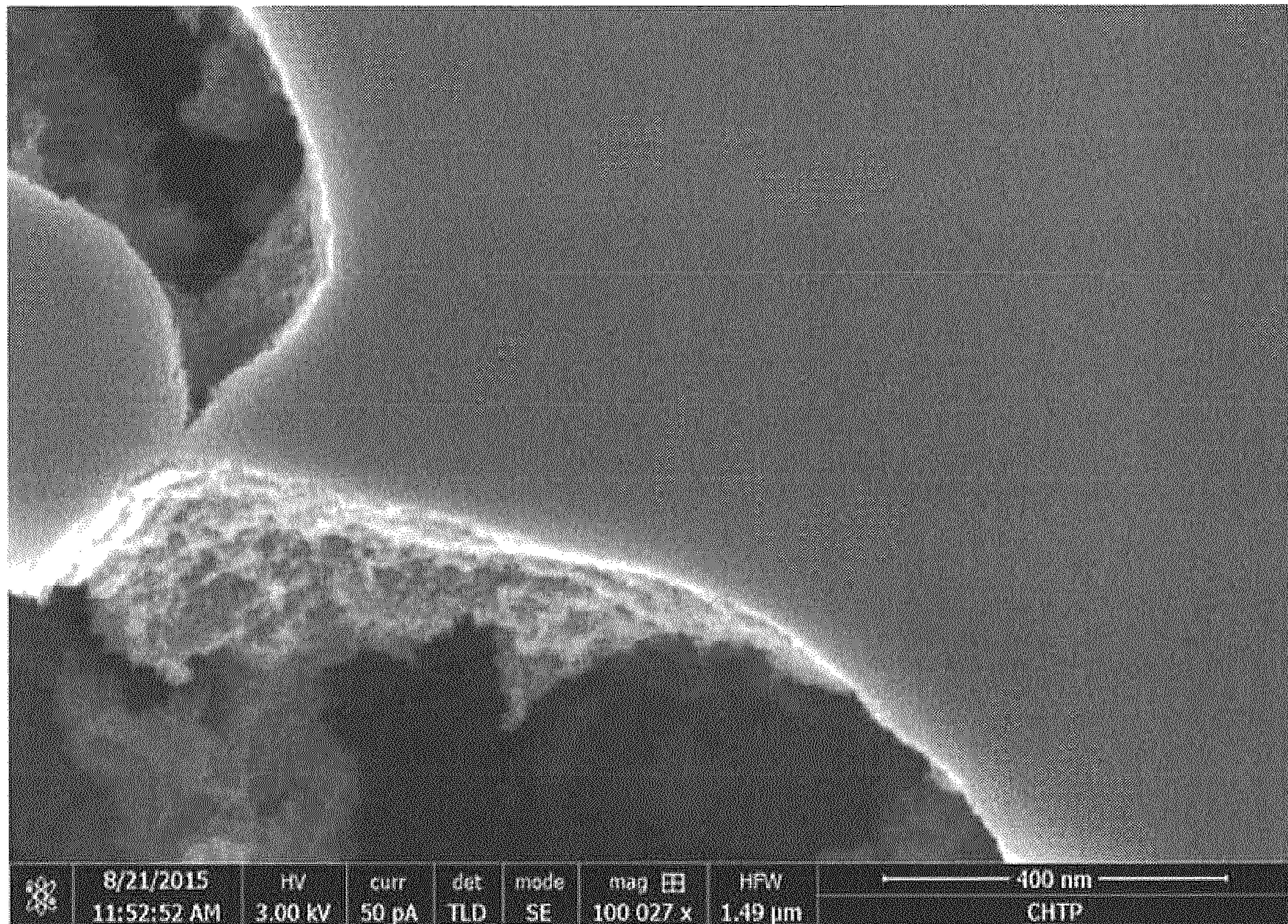


Fig. 25

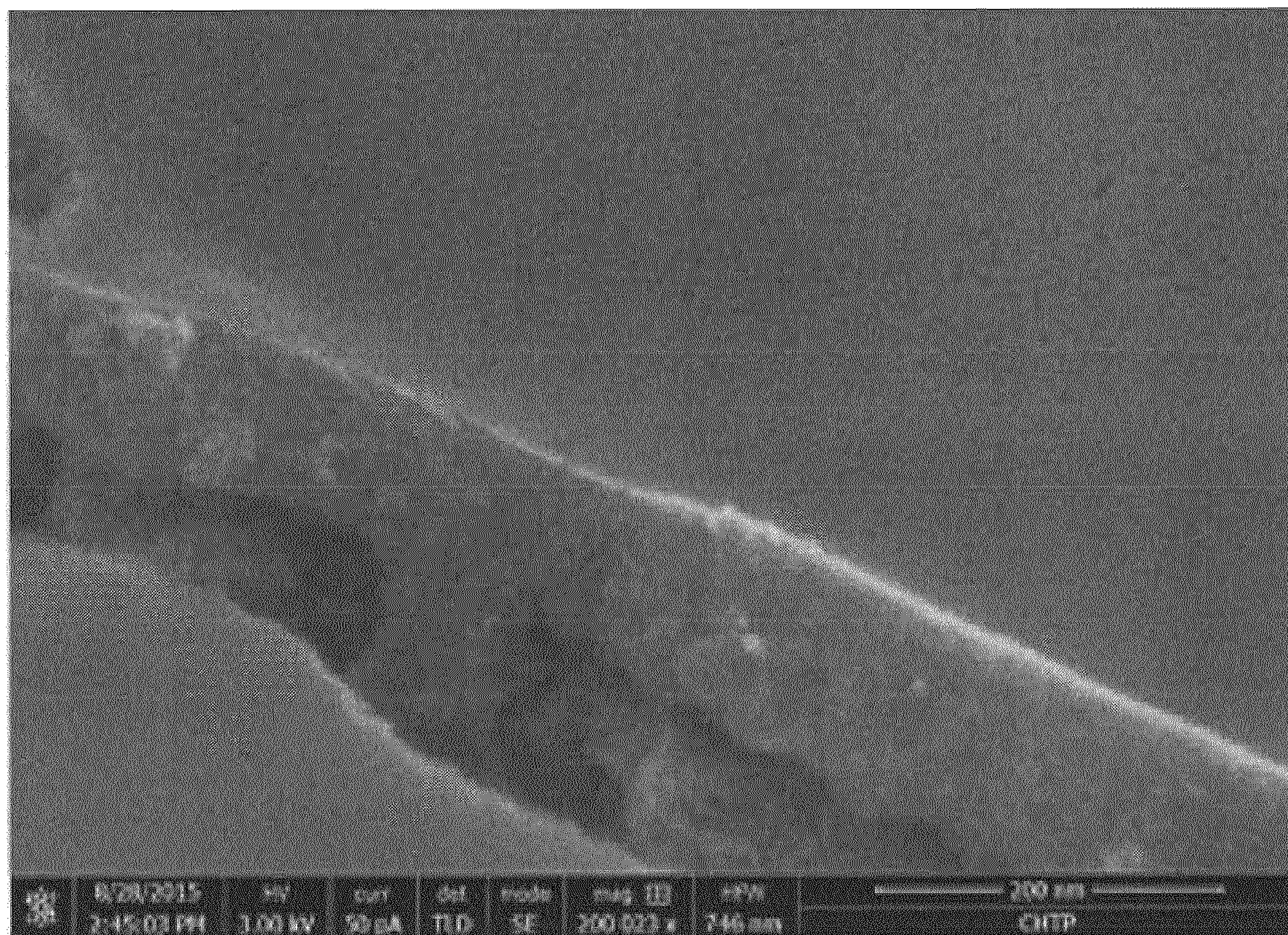


Fig. 26

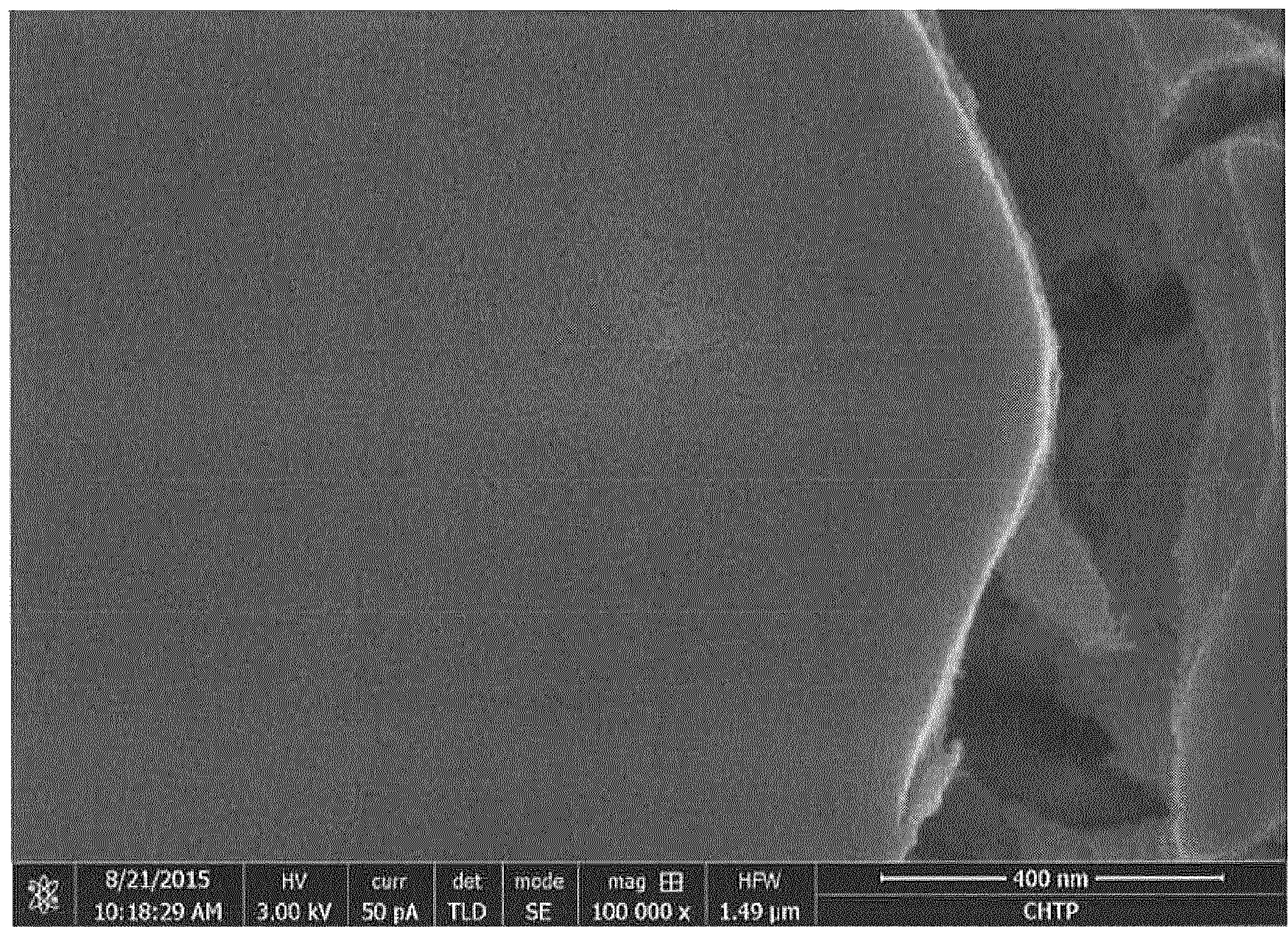


Fig. 27

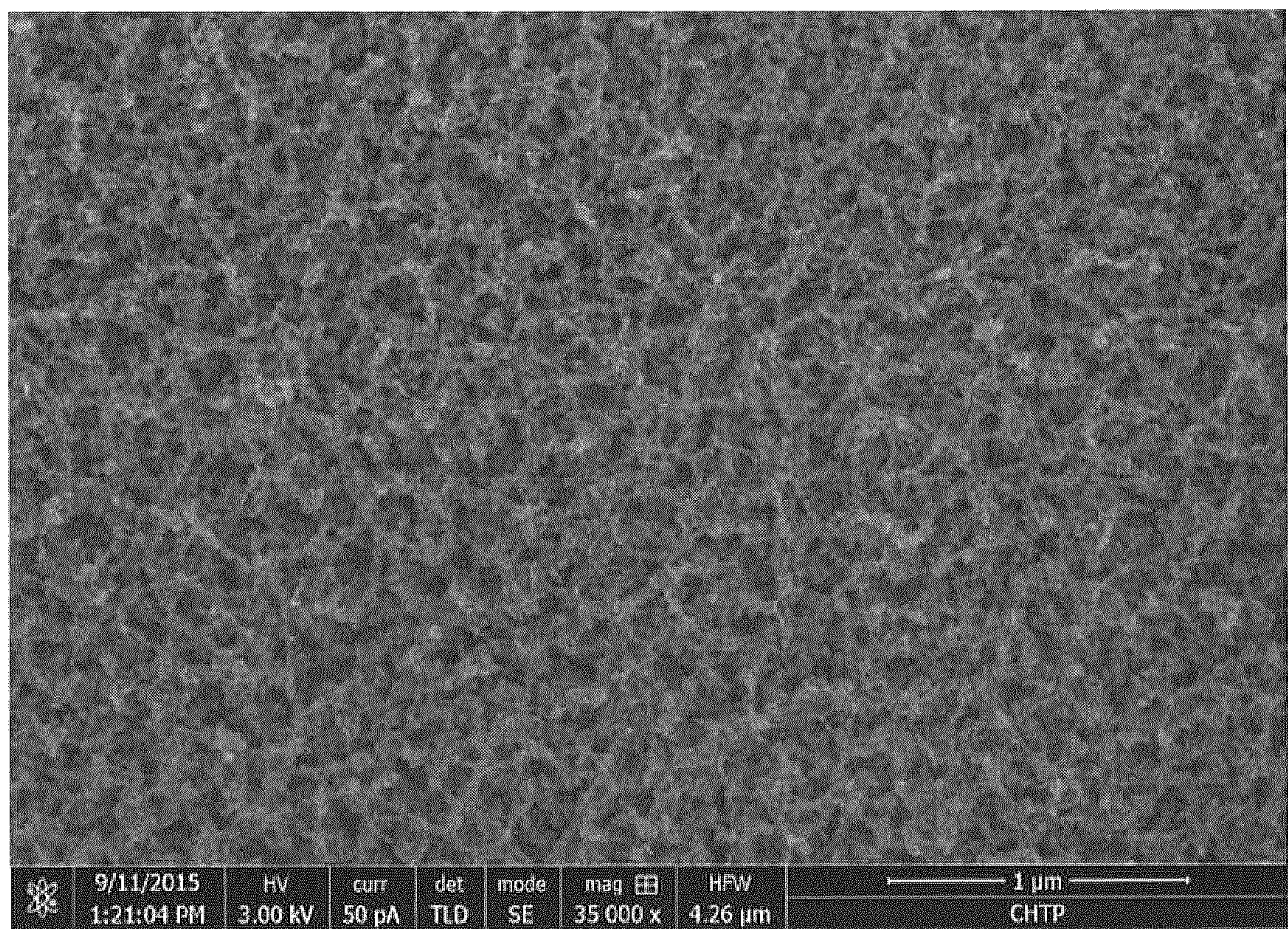


Fig. 28

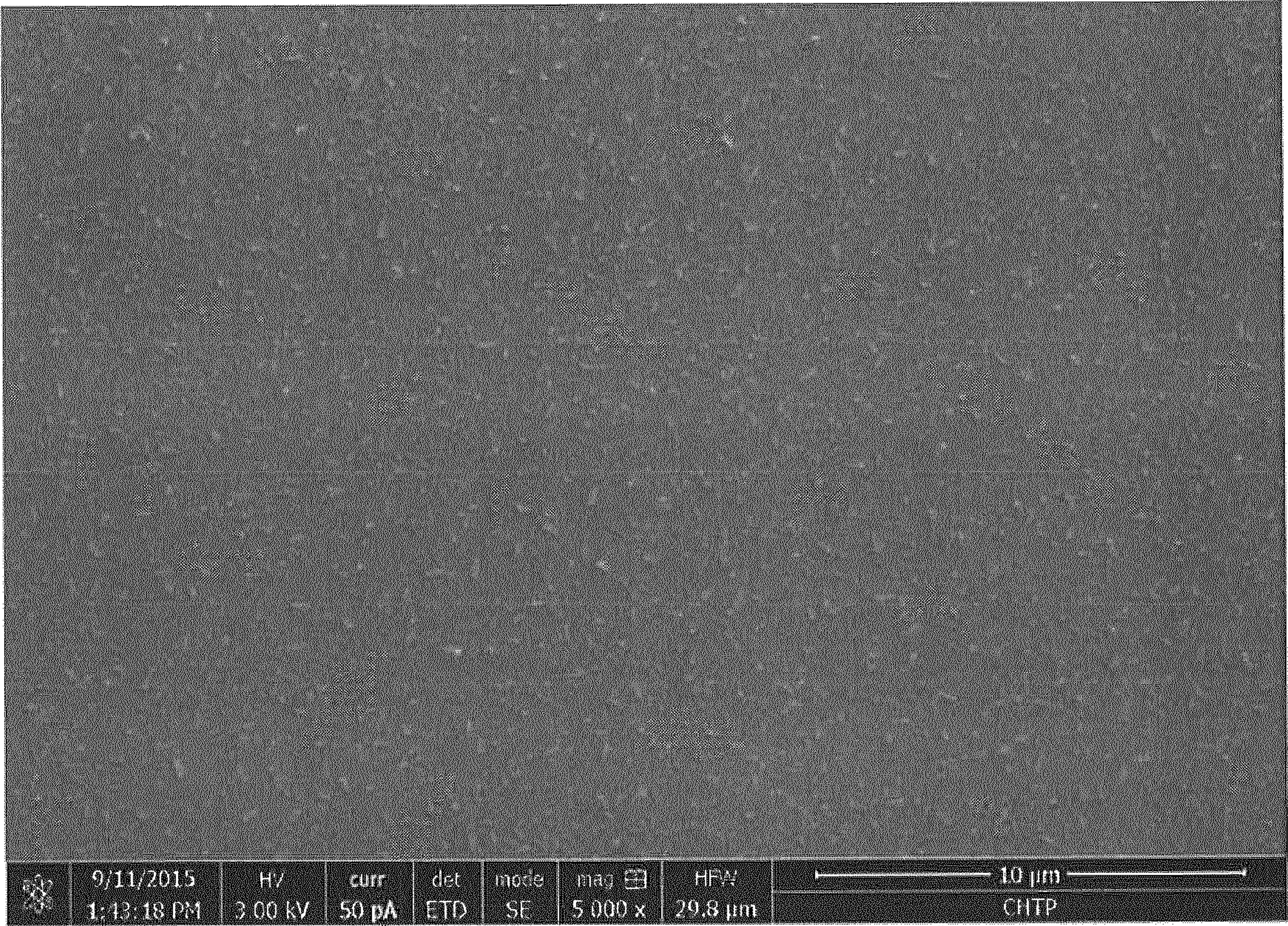


Fig. 29

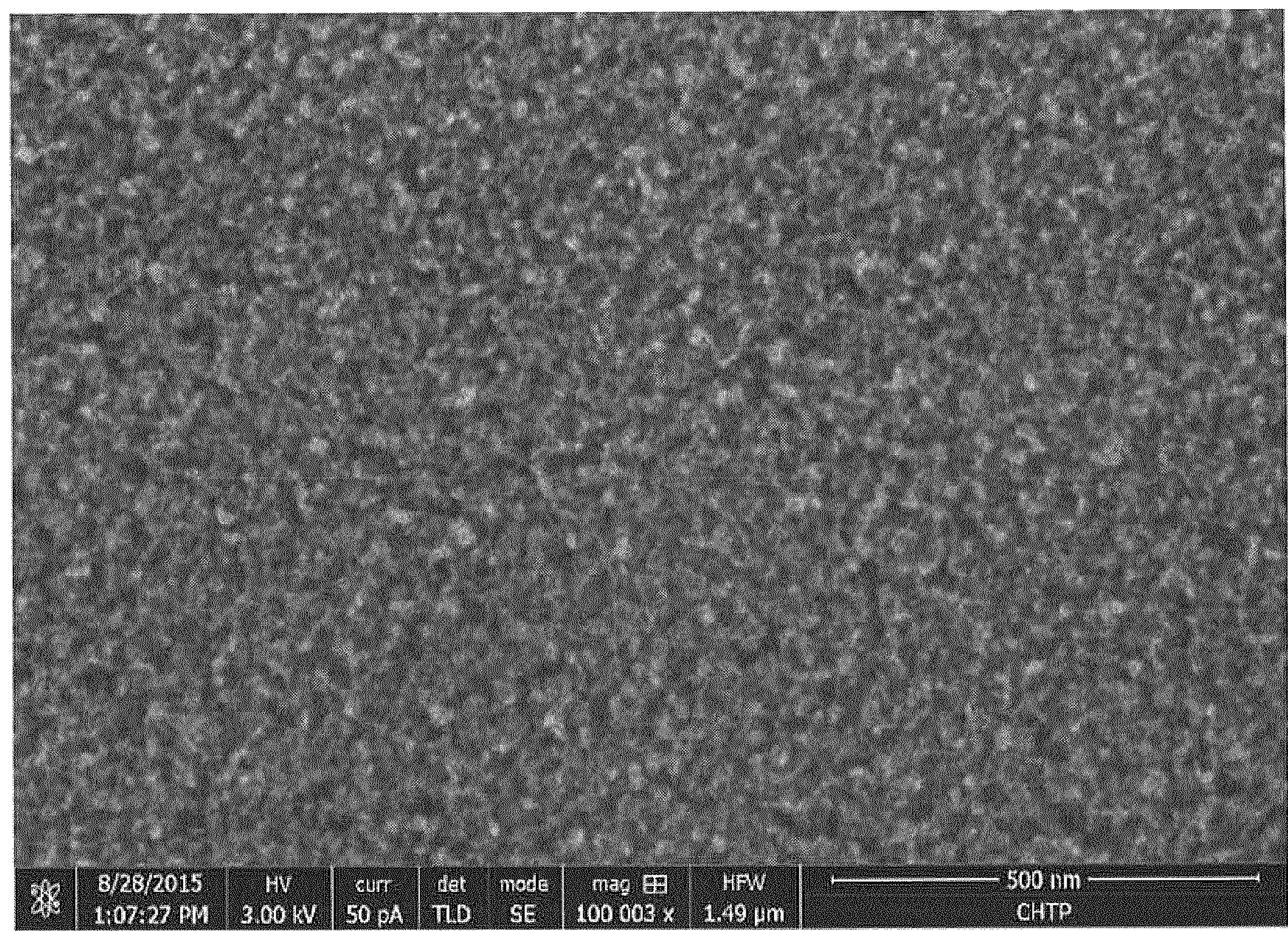


Fig. 30

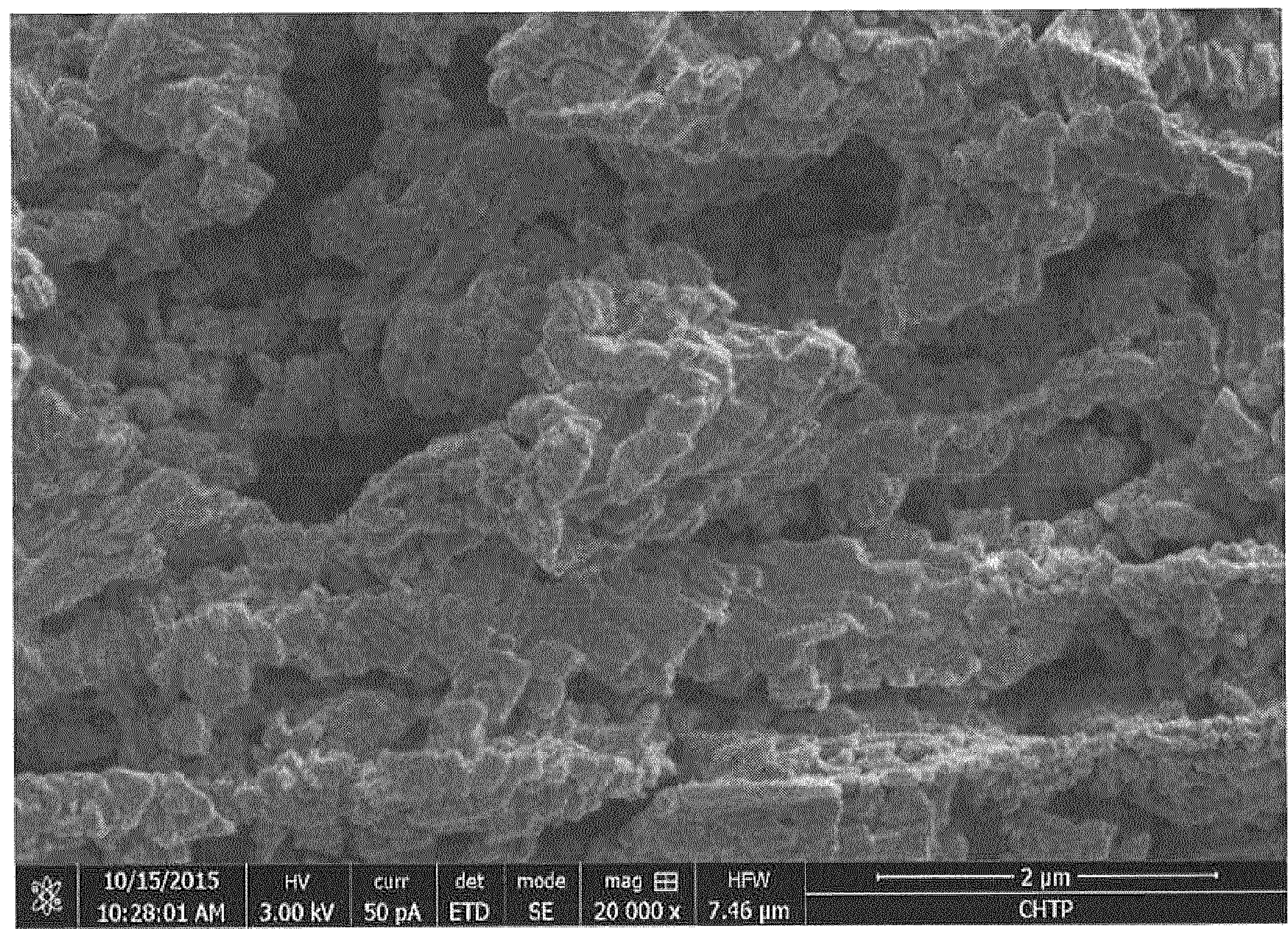
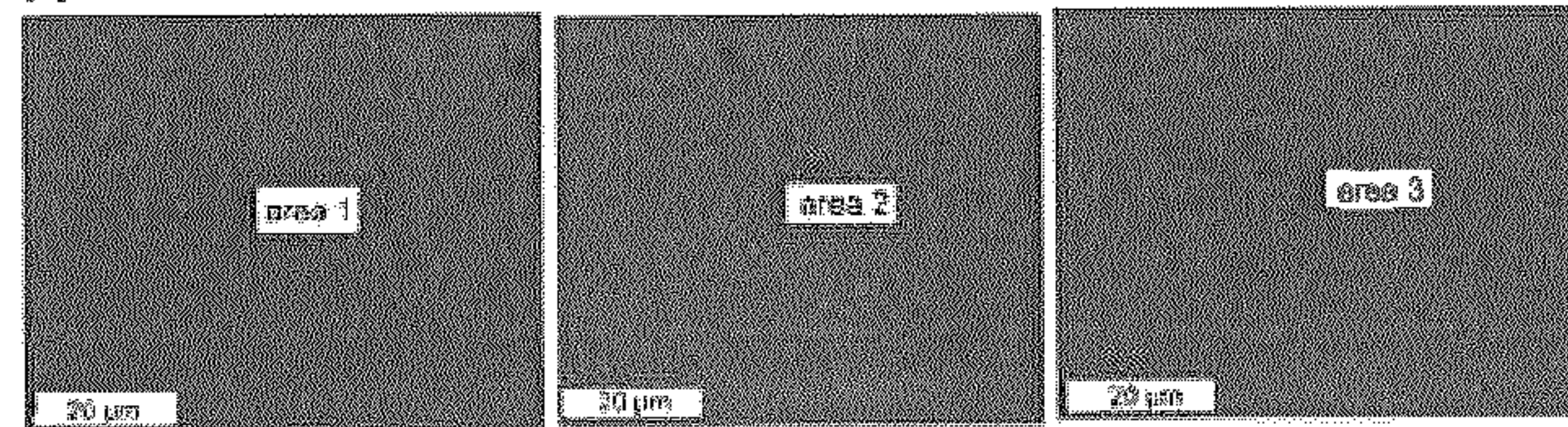


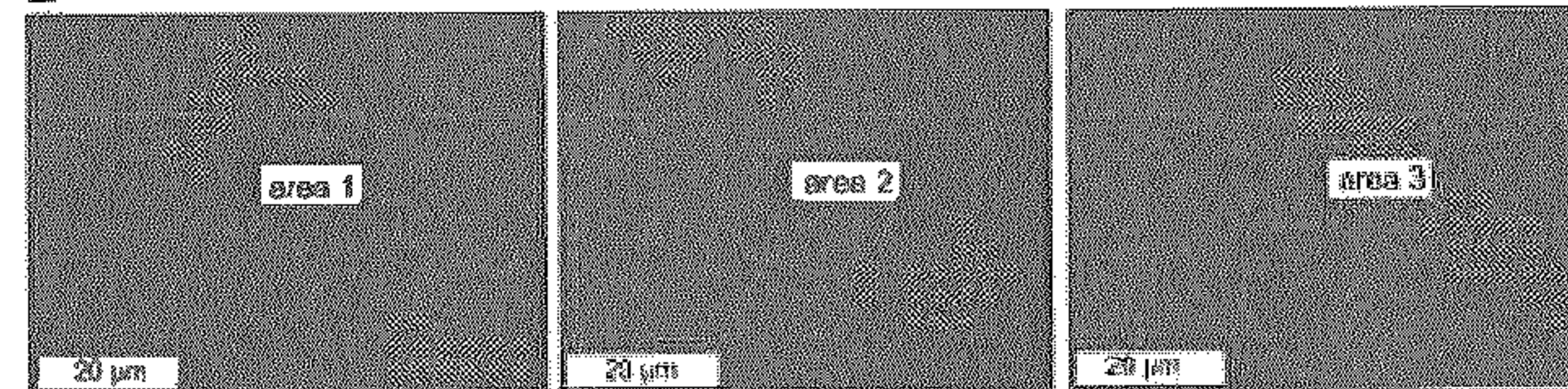
Fig. 31

α -Fe₂Ni₃O_x

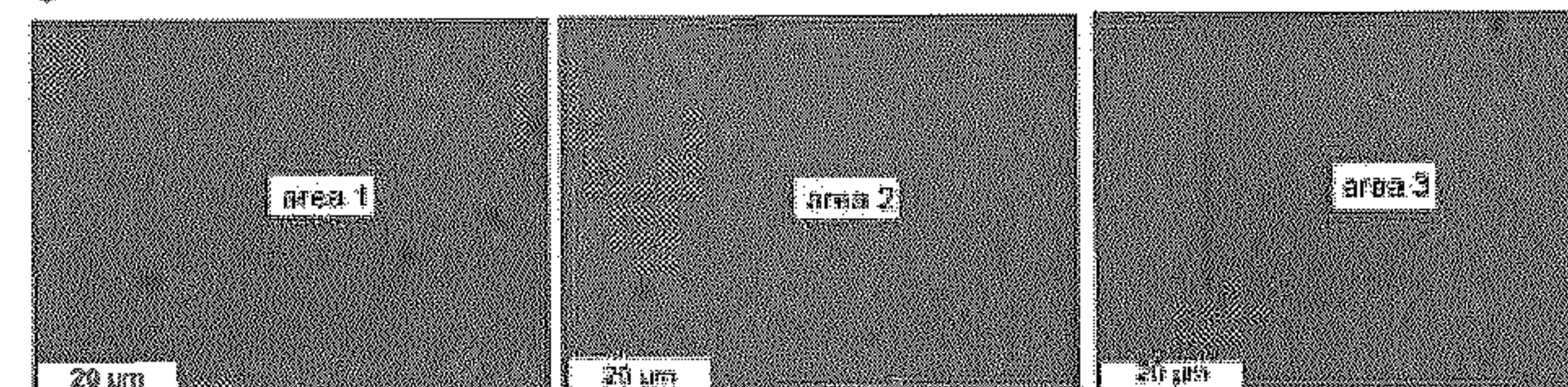
A



B

 α -Fe₂Ni₃

C



D

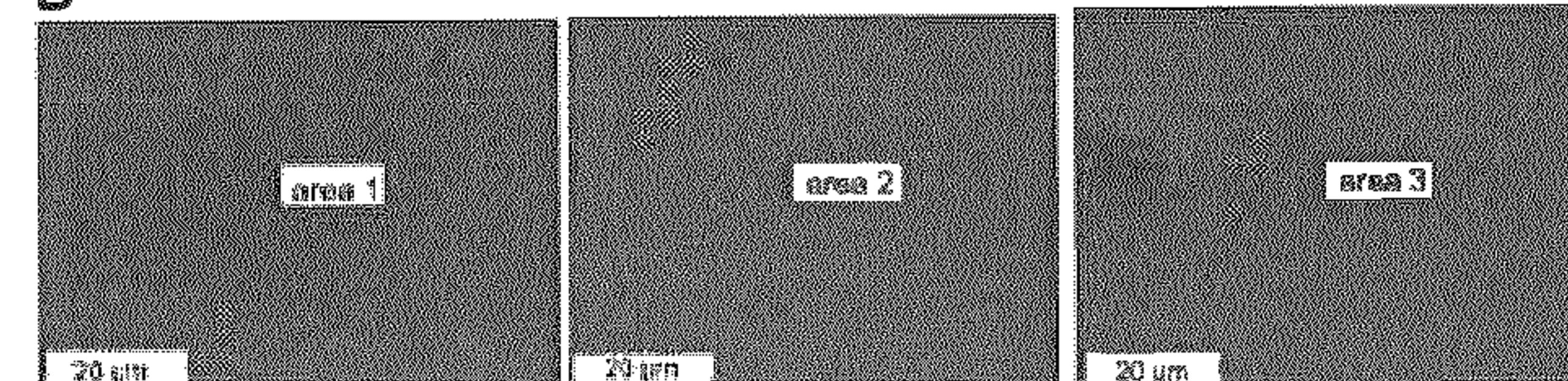


Fig. 32

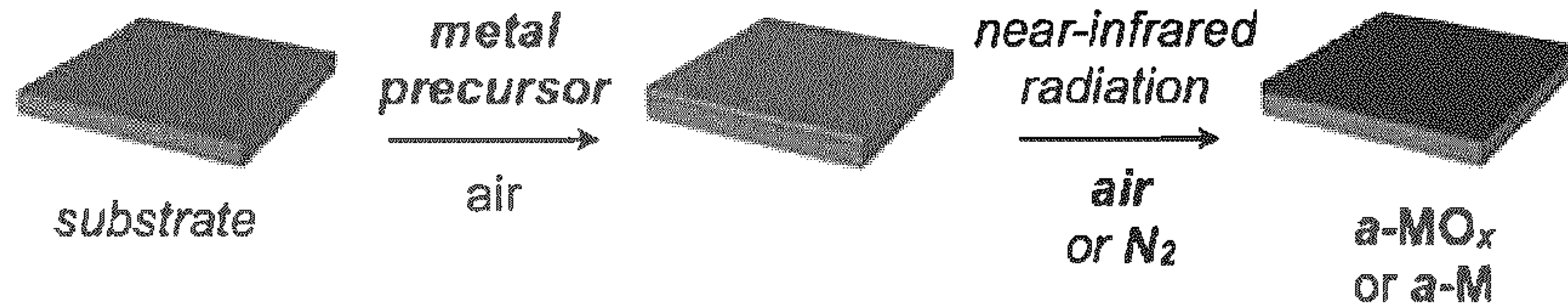


Fig. 1