

CATALYST FOR ELECTROCHEMICAL REDUCTION OF OXYGEN

FIELD OF THE INVENTION

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The invention relates to a catalyst, in particular to an electrocatalyst for oxygen reduction suitable for incorporation in a gas-diffusion electrode structure, and to a method for manufacturing the same.

10 BACKGROUND OF THE INVENTION

Noble metal sulphides are widely known in the field of electrocatalysis; in particular, electrocatalysts based on rhodium and ruthenium sulphide are currently incorporated in gas-diffusion electrode structures for use as oxygen-reducing cathodes in highly
15 aggressive environments, such as in the depolarised electrolysis of hydrochloric acid.

Noble metal sulphide electrocatalysts of the prior art are for instance prepared by sparging hydrogen sulphide in an aqueous solution of a corresponding noble metal precursor, usually a chloride, for instance as disclosed in US 6,149,782, entirely
20 incorporated herein as reference, which is relative to a rhodium sulphide catalyst. The synthesis of noble metal sulphide catalysts with hydrogen sulphide in aqueous solutions is conveniently carried out in the presence of a conductive carrier, in most of the cases consisting of carbon particles. In this way, the noble metal sulphide is selectively precipitated on the carbon particle surface, and the resulting product is a
25 carbon-supported catalyst, which is particularly suitable for being incorporated in gas-diffusion electrode structures characterised by high efficiency at reduced noble metal loadings. High surface carbon blacks, such as Vulcan XC-72 from Cabot Corp./USA are particularly fit to the scope.

30 A different procedure for the preparation of carbon-supported noble metal sulphide catalysts consists of an incipient wetness impregnation of the carbon carrier with a solution of a noble metal precursor salt, for instance a noble metal chloride, followed

by solvent evaporation and gas-phase reaction under diluted hydrogen sulphide at ambient or higher temperature, whereby the sulphide is formed in a stable phase. This is for instance disclosed in US 2004/0242412, relating to a ruthenium sulphide catalyst.

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A more advanced manufacturing process for noble metal sulphide catalysts is further disclosed in US 6,967,185, entirely incorporated herein as reference, and consists of reacting a noble metal precursor with a thio-compound in an aqueous solution free of sulphide ions; in this way, a catalyst substantially equivalent to the one of US
10 6,149,782 is obtained avoiding the use of a highly hazardous and noxious reactant such as hydrogen sulphide.

Although the catalysts disclosed in the above referenced documents proved of utmost importance for the successful commercialisation of hydrochloric acid
15 electrolyzers, they still presents some limitations in terms of activity and of stability to the particularly aggressive environment typical of such application and consisting of a hydrochloric acid solution containing significant amounts of dissolved chlorine and oxygen.

20 As regards the activity, noble metal sulphides precipitated by the methods of the prior art are all prepared by discrete reduction stages producing a mixture of different crystalline phases with different valences and stoichiometry, some of which present a poor electrochemical activity or none at all. Moreover, some of the most active formulation consist of ternary compounds which cannot be reliably prepared by the
25 environmentally friend method of US 6,967,185; the only viable process for obtaining ternary compounds, such as $Ru_xCo_zS_y$ which is also very attractive in terms of cost, is the one disclosed in US 2004/0242412, still relying on hydrogen sulphide as reactant species.

30 As concerns the stability, the above mentioned mixed-valence systems comprised of different crystalline phases typical of the catalysts of the prior art inevitably results to some extent in the formation of less stable phases such as zerovalent metals, metal oxides and non-stoichiometric perovskites. Although rhodium and ruthenium

sulphides are much more stable than any other electrocatalyst for oxygen reduction of the prior art in the hydrochloric acid electrolysis environment, some leakage of noble metal is still detectable, especially when the cell is shut-down for maintenance.

5 OBJECTS OF THE INVENTION

It is one object of the present invention to provide a novel composition of sulphide catalyst for electrochemical reduction of oxygen overcoming the limitations of the prior art; in particular, it is an object of the present invention to provide a more active
10 and stable catalyst for cathodic oxygen reduction in a process of hydrochloric acid electrolysis.

It is another object of the present invention to provide a gas-diffusion electrode incorporating a novel composition of sulphide catalyst useful as cathode in a process
15 of depolarised hydrochloric acid electrolysis.

It is yet another object of the present invention to provide a novel method for manufacturing sulphide catalysts for electrochemical reduction of oxygen.

These and other objects will be clarified by the following description, which shall not
20 be understood as a limitation of the invention, whose extent is exclusively defined by the appended claims.

DESCRIPTION OF THE INVENTION

25 Under a first aspect, the invention consists of a catalyst for electrochemical reduction of oxygen comprising a noble metal sulphide supported as a single well-defined crystalline phase on a conductive carbon; preferably, the noble metal catalyst of the invention is a single crystalline phase of a binary or ternary rhodium or ruthenium sulphide.

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In the case of binary rhodium sulphides expressed by the general formula Rh_xS_y , the inventors have found that the manufacturing methods of the prior art invariably lead to a mixed-valence system at least comprising the species Rh_2S_3 , $Rh_{17}S_{15}$, and

Rh₃S₄ with some amount of metallic rhodium (Rh⁰). Of all these species, Rh₁₇S₁₅ characterised by a crystal lattice corresponding to the (Pm-3m) space group is the most active, followed by monoclinic (C2/m) Rh₂S₃, while the remaining species present little or no activity and in some cases a lesser stability. Rh⁰ is unstable in hydrochloric acid electrolysis conditions, and accounts for the quickest rhodium leaks during operation. In accordance with the processes of US 6,149,782 and US 6,967,185 for example, the typical amount of Rh₁₇S₁₅ is a little higher than 70% of the overall rhodium sulphide species.

The inventors have surprisingly found that a single crystalline phase of (Pm-3m) Rh₁₇S₁₅ on active carbon can be prepared by suitably modifying the environmentally-friendly manufacturing process disclosed in US 6,967,185. The term single crystalline phase is used hereafter to mean a more than 90% pure crystal phase; in the cases of the (Pm-3m) Rh₁₇S₁₅ catalyst according to the invention, the single crystal phase obtained is about 95% pure with no detectable Rh⁰. The method for manufacturing a single crystalline phase of (Pm-3m) Rh₁₇S₁₅ on active carbon comprises the steps of:

- reacting a precursor salt of rhodium, for instance RhCl₃, with a sulphur source such as a thiosulphate or thionate species in the presence of a strong reducing agent and of conductive carbon particles, thus precipitating an amorphous sulphide species on the carbon particles
- recovering the slurry, preferably by filtration
- heat treating the recovered slurry in inert atmosphere at a temperature of 500 to 1250°C until obtaining a single crystalline phase corresponding to (Pm-3m) Rh₁₇S₁₅.

Besides thiosulphates and thionates, other sulphur sources can be used to initiate the metathesis step characterising the method of the invention: tetrathionates such as Na₂S₄O₆ . 2 H₂O and other similar thionate species such as dithionates, trithionates, pentathionates and heptathionates are all fit for this purpose, and also gaseous SO₂ possesses both the reducing power and the sulphur availability to produce amorphous M_xS_y moieties on a selected support.

The support carbon particles have preferably a surface area comprised between 200 and 300 m²/g, and the preferred specific loading of the resulting rhodium sulphide on carbon is comprised between 12 and 18%.

- 5 The sequence of addition of the reactants is critical to obtain the desired product: to the solution containing the suspended carbon particles and the rhodium precursor salt, the selected sulphur source (for instance a tiosulphate or thionate species) is added, so that the metathesis process can initiate. Simultaneously or immediately after, depending on the specific reaction, a strong reducing agent, defined as a
- 10 species with a reduction potential below 0.14 V/SHE, is added in small aliquots. As reducing agent, sodium borohydride (NaBH₄) is preferred, but other suitable reactants include LiAlH₄, hydrazines, formaldehyde and metallic aluminium, zinc or antimony.
- 15 The reducing agent as defined has a reduction potential below the one of S⁰ / S⁻² couple: in this way, it can achieve the instantaneous metathesis of the metal ions and of the thiosulphate part, directly forming amorphous rhodium sulphide on the carbon support particles while preventing the formation of discrete reduction states, which are the main factor controlling the yield and phase distribution of the different
- 20 sulphide moieties.

The method of the invention can be applied to the manufacturing of other single crystalline phases of noble metal sulphides, including not only sulphides of a single metal (binary sulphides) but also of two or more metals (ternary sulphides and so on).

- 25 This proves particularly useful in the case of ruthenium sulphides, because also in this case the method of the invention gives rise to the most active and stable single crystalline phase.

- By applying the method of the invention, binary (RuS₂) and ternary (Ru_xM_zS_y)
- 30 ruthenium sulphides, M being a transition metal preferably selected among W, Co, Mo, Ir, Rh, Cu, Ag and Hg, precipitate in a single crystalline phase with lattice parameters corresponding to a pyrite-type lattice (Pa 3 space group). The resulting (Pa 3) RuS₂ or Ru_xM_zS_y catalysts turn out to be more active and more stable in the

hydrochloric acid electrolysis conditions than mixed-valence ruthenium sulphide systems of the prior art. The preferred catalyst specific loading and selected carbon support are the same applying for rhodium sulphide; also the method of manufacturing is substantially the same, even though suitable temperatures for the thermal treatment may vary from 150 to 1250°C.

The specific reaction pathway of the method according to the invention has the main advantage to intervene on the reduction potentials of the metals and the thionic moieties preventing the formation of discrete reduction states, which are the main factor controlling the yield and proper phase composition of the selected chalcogenide moiety as mentioned above. The method of the invention promotes the instantaneous metathesis of the metal ions and the thionic part. For instance, by reacting the chloride form of a transition metal such as rhodium, whose aqueous hydrolysis gives a pH in the range of 1 to 1.5, with sodium tetrathionate dihydrate ($\text{Na}_2\text{S}_4\text{O}_6 \cdot 2\text{H}_2\text{O}$) and sodium borohydride (NaBH_4) in the presence of carbon, it is possible to directly synthesise amorphous Rh_xS_y supported on carbon. The reaction is conducted at room temperature and can be followed by pH and spot tests. At completion, the slurry is collected and heat-treated in inert environment for a sufficient time to provide the required single phase rhodium sulphide supported catalyst. The same procedure can be used to obtain other binary and ternary sulphides with specific crystal phase distributions. In some cases, the kinetics and yield of the reaction can be improved by adding catalytic amounts of metals such as Al, Sn, Co and others.

The disclosed catalysts are suitable for being incorporated in gas-diffusion electrode structures on electrically conductive webs as known in the art.

The manufacturing of rhodium and of ruthenium sulphide catalysts according to the invention are disclosed in the following examples, which shall not be understood as limiting the invention; suitable variations and modifications may be trivially applied by one skilled in the art to manufacture other carbon supported-single crystalline phase sulphide catalysts of different noble and transition metals relying on the method of the invention without departing from the scope thereof.

BRIEF DESCRIPTION OF THE FIGURE

Figure 1 shows an X-Ray diffractogram of a rhodium sulphide catalyst prepared according to the method of the invention.

EXAMPLE 1

Described herein is a method to precipitate a rhodium sulphide single crystalline phase on carbon according to the method of the invention; precipitation reactions of other noble metal sulphide catalysts (such as the sulphides of ruthenium, platinum, palladium or iridium) only require minor adjustments that can be easily derived by one skilled in the art.

7.62 g of $\text{RhCl}_3 \cdot \text{H}_2\text{O}$ were dissolved in 1 l of deionised water, and the solution was refluxed.

7 g of Vulcan XC 72-R high surface area carbon black from Cabot Corporation were added to the solution, and the mix was sonicated for 1 hour at 40°C.

8.64 g of $(\text{NH}_4)_2\text{S}_2\text{O}_3$ were diluted in 60 ml of deionised water, after which a pH of 7.64 was determined (sulphur source).

4.14 g of NaBH_4 were diluted into 60 ml of deionised water (reducing agent).

The rhodium/Vulcan solution was kept at room temperature and stirred vigorously while monitoring the pH. In this case, the sulphur source and reducing agent solutions were simultaneously added dropwise to the rhodium/Vulcan solution. During the addition, pH, temperature and colour of the solution were monitored. Constant control of the pH is essential in order to avoid the complete dissociation of the thionic compound to elemental S^0 .

The kinetics of the reaction is very fast, therefore the overall precipitation of the amorphous sulphide occurs within few minutes from the beginning of the reaction. Cooling the reaction can help in slowing the kinetics if needed. The reaction was monitored by checking the colour changes: the initial deep pink/orange colour of the

rhodium/Vulcan solution changes dramatically to grey/green (reduction of Rh^{+3} to Rh^{+2} species) and then colourless upon completion of the reaction, thus indicating a total absorption of the products on carbon. Spot tests were also carried out in this phase at various times with a lead acetate paper; limited amount of H_2S was observed due to a minimal dissociation of the thionic species. The precipitate was allowed to settle and then filtered; the filtrate was washed with 1000 ml deionised water to remove any excess reagent, then a filter cake was collected and air dried at 110°C overnight.

- 10 The dried product was finally subjected to heat treatment under flowing argon for 2 hours at 650°C , resulting in a weight loss of 22.15%.

The resulting carbon supported catalyst was first characterised in a corrosion test, to check its stability in a hydrochloric acid electrolysis environment.

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For this purpose, part of the sample was heated to boiling in a chlorine-saturated HCl solution, at the same conditions disclosed in Example 4 of US 6,149,782. The resulting solution was colourless, not even showing the characteristic trace pink of the more stable forms of rhodium sulphide of the prior art.

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- An X-ray diffractogram of the rhodium sulphide catalyst is shown in Figure 1. Rh_xS_y usually obtained by precipitation is characterised by a balanced phase mixture of at least three Rh-S phases: orthorhombic (Pbcn) Rh_2S_3 , monoclinic (C2/m) Rh_3S_4 , and primitive cubic (Pm-3m) $\text{Rh}_{17}\text{S}_{15}$. The Rh_2S_3 phase is an electronic insulator built of alternating RhS_6 octahedra. The average Rh-Rh bond distance of $3.208 \text{ \AA}$ (compared to $2.69 \text{ \AA}$ in fcc Rh metal) thus removes any possibility of direct Rh-Rh bonding. In contrast, the $\text{Rh}_{17}\text{S}_{15}$ phase possesses semiconductor properties at room temperature. In addition, $\text{Rh}_{17}\text{S}_{15}$ consists of Rh_8 octahedra with an average Rh-Rh distance of $2.59 \text{ \AA}$. The Rh_3S_4 phase, with its metallic Rh_6 octahedra eaves, is an active site for O(H) adsorption. The left part of the figure shows the diffractogram on top and the characteristic peaks of the different Rh-S phases below: the comparison clearly shows how the $\text{Rh}_{17}\text{S}_{15}$ phase is absolutely predominant (>95%) with a characteristic set of 4 peaks at $2\theta = 37.38 - 40.68^\circ$ representing the (104), (114),
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(223), and (024) reflections, and the high intensity peaks at 47.64 and 52.16° indicating the (333) and (044) reflections.

This is even more evident in the right part of the figure, where the characteristic peaks of the Rh₁₇S₁₅ phase are superposed to the XRD spectrum.

EXAMPLE 2

A ruthenium cobalt ternary sulphide (3:1) catalyst was prepared in a similar manner as the one of Example 1, the difference being that the thionic reagent is now part of the metal ion solution, thus the metathesis reaction occurs in-situ on the metal ion sites.

7.62 g of RuCl₃·xH₂O were dissolved in 1 l of deionised water, and the solution was refluxed.

2.46 g of CoCl₂·xH₂O were also added to the Ru containing solution and refluxed as above.

8 g of Vulcan XC72-R high surface area carbon black from Cabot Corporation were added to the solution, and the mix was sonicated for 1 hour at 40°C.

17.5 g of (NH₄)₂S₂O₃ were diluted in 100 ml of deionised water, after which a pH of 7.72 was determined, then added to the catalyst/Vulcan solution (sulphur source).

6.54 g of NaBH₄ were diluted into 100 ml of deionised water (reducing agent).

The sulphur source solution containing ruthenium, cobalt and Vulcan carbon black was kept at room temperature and stirred vigorously while monitoring the pH. Once the reducing agent solution was prepared, it was added dropwise to the sulphur source solution. During the addition of the reagents, pH, temperature and colour of the solution were monitored. Constant control of the pH is essential in order to avoid the complete dissociation of the thionic compound to elemental S⁰.

As for Example 1, also in this case the kinetics of the reaction is very fast therefore the overall precipitation of the amorphous sulphide occurs within few minutes from the beginning of the reaction. Cooling the reaction can help in slowing the kinetics if

needed. The reaction was monitored by checking the colour changes: the initial deep brown/orange colour of the initial solution changes dramatically to colourless upon completion of the reaction, thus indicating a total absorption of the products on the carbon. Spot tests were also carried out in this phase at various times with a lead acetate paper; limited amount of H_2S was observed due to a minimal dissociation of the thionic species. Moreover, no Co^0 (metal) was observed; spot test for such particular metal is very straightforward because of the magnetic properties of Co^0 . The precipitate was allowed to settle and then filtered; the filtrate was washed with 1000 ml deionised water to remove any excess reagent, then a filter cake was collected and air dried at 110°C overnight.

The dried product was finally subjected to heat treatment under flowing nitrogen for 2 hours at 500°C , resulting in a weight loss of 32.5%.

The resulting carbon supported catalyst was subjected to the same corrosion and electrochemical tests of the previous example, showing identical results.

Actual performances in hydrochloric acid electrolysis of the catalyst prepared according to the method of the invention and incorporated in a gas-diffusion structure on a conductive web as known in the art were also checked.

EXAMPLE 3

Different samples of the catalysts of Examples 1 and 2 were prepared, mixed to a PTFE dispersion and incorporated into conventional flow-through gas diffusion electrode structures on carbon cloth. All the electrodes were compared to a standard state-of-the-art supported Rh_xS_y electrode for hydrochloric acid electrolysis, according to the teaching of US Patent 6,149,782 and 6,967,185 (Sample 0). Such electrodes were tested as oxygen-consuming cathodes in a 50 cm^2 active area laboratory cell against a standard anode, making use of a by-product aqueous hydrochloric acid solution from an isocyanate plant. The overall cell voltage was recorded at two different current densities, namely 3 and 6 kA/m^2 , and the corresponding values are reported in Table 1.

Sample ID	voltage at 3 kA/m ²	voltage at 6 kA/m ²
0	1.16	1.45
Example 1	1.10	1.37
Example 2	1.11	1.41

All of the tested electrode samples showed an excellent catalytic activity, resulting in a sensible voltage decrease with respect to the electrode activated with a rhodium sulphide catalyst of the prior art (sample 0).

Equivalent rhodium sulphide catalysts were obtained also by using sodium trithionate, tetrathionate and heptathionate precursors previously prepared according to known procedures, with minor adjustments easily derivable by one skilled in the art. Analogous corrosion and electrochemical results were obtained also in these cases.

The above description shall not be understood as limiting the invention, which may be practised according to different embodiments without departing from the scopes thereof, and whose extent is solely defined by the appended claims.

In the description and claims of the present application, the word “comprise” and its variations such as “comprising” and “comprises” are not intended to exclude the presence of other elements or additional components.

CLAIMS

1. A catalyst for electrochemical reduction of oxygen comprising a noble metal sulphide single crystalline phase supported on a conductive carbon.
2. The catalyst of claim 1 wherein said noble metal sulphide is a rhodium or ruthenium sulphide.
3. The catalyst of claim 2 wherein said single crystalline phase is (Pm-3m) $\text{Rh}_{17}\text{S}_{15}$.
4. The catalyst of claim 2 wherein said noble metal sulphide is a sulphide of ruthenium and optionally of an additional transition metal M and said single crystalline phase is (Pa 3) RuS_2 or $\text{Ru}_x\text{M}_z\text{S}_y$.
5. The catalyst of claim 4 wherein said additional transition metal is selected from the group consisting of W, Co, Mo, Ir, Rh, Cu, Ag, Hg.
6. The catalyst of any one of claims 3 to 5 wherein said conductive carbon has a surface area of 200 to 300 m^2/g and the specific loading of said noble metal sulphide on said conductive carbon is 12 to 18%.
7. A gas diffusion electrode comprising the catalyst of any one of the previous claims on a conductive web.
8. A method for manufacturing the catalyst of any one of claims 1 to 6, comprising the steps of:
 - reacting a precursor salt of a noble metal and optionally of at least one additional transition metal with a sulphur source in the presence of conductive carbon particles in an aqueous solution
 - precipitating said noble metal sulphide on said conductive carbon particles by either simultaneously or subsequently adding a reducing

agent having a reduction potential below 0.14 V/SHE to said aqueous solution

- recovering and heat treating the resulting slurry in inert atmosphere until obtaining a single crystalline phase.

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9. The method of claim 8 wherein said sulphur source is a thiosulphate or thionate species.

10. The method of claim 8 or 9 wherein said noble metal is rhodium.

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11. The method of claim 8 or 9 wherein said noble metal is ruthenium and said at least one additional metal is selected from the group consisting of W, Co, Mo, Ir, Rh, Cu, Ag, Hg.

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12. The method of any one of claims 8 to 11 wherein said slurry is recovered by filtering and said heat treatment is carried out at 150 to 1250°C.

13. The method of any one of claims 8 to 12 wherein said reducing agent is NaBH_4 .

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