

1 **Enhanced electrochemical reduction of hydrogen peroxide by Co<sub>3</sub>O<sub>4</sub> nanowire**  
2 **electrode**

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2

3 **Abstract**

4 Crystalline  $\text{Co}_3\text{O}_4$  nanowire arrays with different morphologies grown on Ni foam were  
5 investigated by varying the reaction temperature, the concentration of precursors, and  
6 reaction time. The  $\text{Co}_3\text{O}_4$  nanowires synthesized under typical reaction condition had a  
7 diameter range of approximately 500–900 nm with a length of 17  $\mu\text{m}$ . Electrochemical  
8 reduction of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) of the optimized  $\text{Co}_3\text{O}_4$  nanowire electrode was  
9 studied by cyclic voltammetry. A high current density of 101.8  $\text{mA cm}^{-2}$  was obtained at  
10 -0.4 V in a solution of 0.4 M  $\text{H}_2\text{O}_2$  and 3.0 M NaOH at room temperature compared to  
11 85.8  $\text{mA cm}^{-2}$  at -0.35 V of the  $\text{Co}_3\text{O}_4$  nanoparticle electrode. Results clearly indicated  
12 that the Ni foam supported  $\text{Co}_3\text{O}_4$  nanowire electrode exhibited superior catalytic activity  
13 and mass transport kinetics for  $\text{H}_2\text{O}_2$  electrochemical reduction.

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15 **Keywords:**  $\text{Co}_3\text{O}_4$ ; Nanowire arrays; Ni foam;  $\text{H}_2\text{O}_2$  electrochemical reduction

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## 1 **1. Introduction**

2 Recently, the development of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) as an oxidant for low-  
3 temperature liquid-based fuel cells has attracted significant attention due to lower  
4 activation energy, better stability, and ease of handling and storage compared to oxygen  
5 based fuel cells [1-3]. Lao et al. has shown that electrochemical reduction of  $\text{H}_2\text{O}_2$  has  
6 faster kinetics than that of oxygen [4]. Yin et al. has demonstrated a direct  
7 hydrazine/ $\text{H}_2\text{O}_2$  fuel cell exhibiting an open circuit voltage (OCV) of  $\sim 1.6$  V and a high  
8 power density of  $470 \text{ mW cm}^{-2}$  compared to that with oxygen oxidant (OCV $\sim 0.9$  V and  
9  $73.9 \text{ mW cm}^{-2}$ ) [5]. To date, noble metals such as Pt, Pd, Ir, Au, and Ag are the dominant  
10 catalysts for electrochemical reduction  $\text{H}_2\text{O}_2$  owing to the high efficiency and stability [6-  
11 9]. However, the expensive cost and scarcity of noble metal resources hinder their  
12 practical applications. Therefore, current research focuses on the electrochemical  
13 reduction of  $\text{H}_2\text{O}_2$  using transitional metal oxides such as nickel oxide, iron oxide, copper  
14 oxide due to their low cost, high abundance, and high electrocatalytic reaction [10].

15

16 Among the transitional metal oxides, cobalt oxide ( $\text{Co}_3\text{O}_4$ ) has been extensively studied  
17 because of its superior catalytic properties arise from its efficient electron transportation  
18 between  $\text{Co}^{2+}$  and  $\text{Co}^{3+}$  ions [11, 12]. However,  $\text{Co}_3\text{O}_4$  catalysts usually suffer from the  
19 poor electrical conductivity and the dissolution or agglomeration during electrochemical  
20 processes [13]. Therefore, mixing  $\text{Co}_3\text{O}_4$  catalysts with conductive carbon-based  
21 materials such as carbon nanotubes, graphene, and carbon foam is proposed to improve  
22 the conductivity of the  $\text{Co}_3\text{O}_4$  hybrid catalysts [14]. However, such mixing approach  
23 involves the use of an organic binder, which will decrease the effective surface area of

1 the  $\text{Co}_3\text{O}_4$  catalysts [15]. Accordingly, a binder-free approach by directly growing the  
2 electrocatalyst materials on a current collector such as carbon-based materials has proved  
3 to enhance the cycling stability of the electrocatalysts [16, 17]. Also, one-dimensional  
4 (1D) nanostructure have been reported to be a promising morphology for high  
5 electrochemical performance owing to their sufficient exposed surface, efficient ion  
6 transfer and rapid electron transport [18, 19].

7  
8 In this work, various synthesis conditions including the influence of reaction temperature,  
9 the concentration of precursors, and reaction time on the morphology of 1D  $\text{Co}_3\text{O}_4$   
10 nanostructures grown on Ni foam were comprehensively investigated. The optimized  
11  $\text{Co}_3\text{O}_4$  nanowire electrode was selected to study the electrochemical reduction of  $\text{H}_2\text{O}_2$  in  
12 alkaline medium. For comparison, the electrochemical reduction of  $\text{H}_2\text{O}_2$  in conventional  
13 powdery  $\text{Co}_3\text{O}_4$  nanoparticle electrode was studied. The  $\text{Co}_3\text{O}_4$  nanowire electrode  
14 delivered a high current density of  $101.8 \text{ mA cm}^{-2}$  at  $-0.4 \text{ V}$  in a solution of  $0.4 \text{ M H}_2\text{O}_2$   
15 and  $3.0 \text{ M NaOH}$  at room temperature compared to  $85.8 \text{ mA cm}^{-2}$  at  $-0.35 \text{ V}$  of the  $\text{Co}_3\text{O}_4$   
16 nanoparticle electrode.

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## 18 **2. Experimental**

19

### 20 **2.1. Ni Foam Supported $\text{Co}_3\text{O}_4$ Nanowire Arrays**

21 Ni foam substrate (110 PPI,  $320 \text{ g m}^{-2}$ ; Artenano Company Limited, HK) was cleaned in  
22 acetone for 10 min, then etched with  $6.0 \text{ M HCl}$  for 30 min. After thoroughly rinsing with  
23 water, the Ni foam was soaked in  $0.1 \text{ mM NiCl}_2$  for 8 h and extensively rinsed with water.

1 Various amount of  $\text{Co}(\text{NO}_3)_2$  and  $\text{NH}_4\text{NO}_3$  were added in a solution consisting of  
2 deionized water and ammonia (30 wt%). The homogeneous solution containing 0.2 M  
3  $\text{Co}(\text{NO}_3)_2$  and 0.1 M  $\text{NH}_4\text{NO}_3$  was magnetically stirred for 20 min in air at room  
4 temperature until the pink color solution was gradually turned to black color. Such  
5 change of color indicates that  $\text{Co}(\text{II})$  ions were partially oxidized to  $\text{Co}(\text{III})$  ions in the  
6 solution through the uptake of oxygen. Ammonia added to the solution might enhance the  
7 oxidation of  $\text{Co}(\text{II})$  ions to  $\text{Co}(\text{III})$  ions [20]. The pretreated Ni foam and the obtained  
8 homogeneous solution were then transferred to a Teflon-lined stainless-steel autoclave,  
9 which was sealed and kept at different temperatures and maintained for different reaction  
10 times. To investigate the impact of various synthesis parameters on the morphology of  
11 the nanowire grown on the Ni foam, a series of conditions were tested and summarized in  
12 Table 1. After the reaction, the Ni foam with as-synthesized products was taken out from  
13 the solution and thoroughly washed with water, dried at 80 °C. Then, the Ni foam with  
14 as-grown  $\text{Co}_3\text{O}_4$  precursors were calcined at 300° C for 2 h. Notably, the merging of  
15  $\text{Co}_3\text{O}_4$  nanowires occurred when the thermal treatment temperature was higher than 300°  
16 C [21]. For comparison, the morphology of the nanowire arrays was examined using  
17 scanning electron microscopy (SEM, JEOL JSM-5600) and transmission electron  
18 microscopy (TEM, FEI Teccai G2 S-Twin, Philips). The structure was determined using  
19 an X-ray diffractometer (XRD, Siemens D500). The  $2\theta$  scan range was from 10° to 80°  
20 with a scan rate of 5 °  $\text{min}^{-1}$  and a step width of 0.02°.

21

## 22 **2.2. $\text{H}_2\text{O}_2$ Electroreduction**

1 Cyclic voltammetric tests were conducted on an IVIUM nSTAT electrochemical station.  
2 Ni foam supported binder-free  $\text{Co}_3\text{O}_4$  nanowire electrode and powdery  $\text{Co}_3\text{O}_4$   
3 nanoparticle electrode were working electrodes. The powdery  $\text{Co}_3\text{O}_4$  nanoparticle  
4 electrode was prepared by mixing the active material (5 mg), acetylene black, and  
5 polytetrafluorene-ethylene (PTFE) binder at a weight ratio of 80:15:5 and dispersing the  
6 mixture in ethanol to produce a homogeneous paste. The mixture was carefully placed  
7 onto nickel foam ( $1\text{ cm} \times 1\text{ cm} \times 0.2\text{ cm}$ ), and then dried in a vacuum oven at  $80\text{ }^\circ\text{C}$   
8 before pressing under a pressure of 20 MPa. A glassy carbon rod behind a D-porosity  
9 glass frit and a saturated Ag/AgCl, KCl electrode was employed as the counter and  
10 reference electrodes, respectively. All electrochemical tests were performed at room  
11 temperature. The electrolyte was a 3.0 M aqueous NaOH solution made using analytical  
12 grade chemical reagents.

13

### 14 **3. Results and discussion**

15

16 To study the effect of time on the morphology of the nanowire arrays grown on the Ni  
17 foam, different reaction times were tested ranging from 3 to 18 h (Table 1, Samples 1–4).  
18 Figure 1a-c shows the morphological and structural evolution of the nanowires grown on  
19 the Ni foam at different reaction times. The shiny Ni foam substrate turned black after  
20 nanowire growth. Both the size and uniformity of the nanowires increased with  
21 prolongation of reaction time. For the reaction time of 12 h (Sample 3), the  $\text{Co}_3\text{O}_4$   
22 nanowires were structurally uniform and had diameters of approximately 500–900 nm  
23 and lengths of up to  $17\text{ }\mu\text{m}$ . However, when the reaction time reached 18 h, the nanowires

1 (Fig. 1d, Sample 4) became slightly lengthened, and the uniformity became degraded. A  
2 number of nanoparticles were deposited onto the surface of the nanowires. The reason  
3 might be that some high-energy sites were formed due to the effect of ammonia and  
4 vapor-liquid equilibrium, causing Co ions to nucleate spontaneously onto these active  
5 sites and to form nanoparticles. It was reported that hydrazine hydrate as a bidentate  
6 ligand can play a structure-directed role in the formation of  $\beta$ -Co(OH)<sub>2</sub> nanocolumns [22].  
7 Ammonia is expected to play a similar role in the nanowire growth because ammonia is a  
8 unidentate ligand and it can form complexes with Co(II) ions and Co(III) ions.

9

10 The proposed evolution process is as follows. At the early stage of the reaction, the  
11 adsorption of Co(II) cations on the Ni foam increased the local cation concentration and  
12 formed the nuclei. The dominant  $\beta$ -Co(OH)<sub>2</sub> nanowires were then formed from the nuclei  
13 during the initial 6 h reaction [23, 24] (Samples 1–2). When the reaction time was  
14 prolonged to 12 h, the surface of nanowire became granular. A clear Co<sub>3</sub>O<sub>4</sub> spinel phase  
15 was identified, as supported by the XRD pattern (Fig. 4a). The granular morphology of  
16 the Co<sub>3</sub>O<sub>4</sub> nanowires was due to the solid-state reaction between the  $\beta$ -Co(OH)<sub>2</sub>  
17 nanowires and the dissolved oxygen in the solution. These results, combined with the  
18 XRD results (Fig. 4a), confirm that the as-prepared nanowires consisted of brucite  $\beta$ -  
19 Co(OH)<sub>2</sub> and spinel Co<sub>3</sub>O<sub>4</sub> phases, which suggest the partial oxidation of Co(II) ions to  
20 Co(III) ions during the nanowire growth [21]. The oxidation reaction from  $\beta$ -Co(OH)<sub>2</sub> to  
21 Co<sub>3</sub>O<sub>4</sub> was considered as energetically favored transformation [25]. Notably, the  $\beta$ -  
22 Co(OH)<sub>2</sub> nanowire was transformed to Co<sub>3</sub>O<sub>4</sub> nanowire without a significant increase in  
23 diameter. Figure 2 shows the Co<sub>3</sub>O<sub>4</sub> samples synthesized under different concentrations

1 of precursors (Samples 5–8). The results suggest that low reactant concentration of the  
2 reactant (Sample 5) could not sustain the growth of nanowires but only caused the  
3 formation of compact and non-uniform nanoplates on the surface of the Ni foam. The  
4 mechanism of nanoplate growth was complicated and influenced by various factors. The  
5 dominant phase of the as-prepared nanocrystal produced in the initial stage of reaction  
6 (non-calcined) was the brucite  $\beta$ -Co(OH)<sub>2</sub> phase, which had a layered structure and  
7 comprised sheets of hexagonally close-packed OH ions with one Co(II) ions bonded to  
8 six OH ions. These  $\beta$ -Co(OH)<sub>2</sub> sheets were bonded to one another by weak OH-OH  
9 dipole interactions. Therefore, brucite crystals have the tendency to grow into thin  
10 nanoplates. When the concentration of reactants was low (Sample 5), the amount of  
11 reactant could not sustain the growth of nanowires. Thus, a compact thin film of  $\beta$ -  
12 Co(OH)<sub>2</sub> nanoplates were produced. After calcination in air,  $\beta$ -Co(OH)<sub>2</sub> nanoplates were  
13 transformed into Co<sub>3</sub>O<sub>4</sub> nanoplates without apparent change in morphology. In general,  
14 materials with hexagonal structure are favored to form 1-D nanostructures under a  
15 suitable reaction condition [24]. When the concentration of reactants increases, uniform  
16 nanowires are formed instead of nanoplates. However, a higher concentration of reactants  
17 (Fig. 2d, Sample 8) can cause the nanowires to become bigger or several single ones to  
18 merge. These phenomena might be caused by the rapid mass transfer and a large amount  
19 of high-energy sites on the surface of the as-prepared nanowires. When the concentration  
20 of reactants (Fig. 2c, Sample 7) was a little lower than the typical concentration (Sample  
21 3), uniform and smooth nanowires were successfully obtained. However, the number  
22 density of the nanowires was sparser than the ones synthesized under the typical  
23 condition (Sample 3). The results suggest that the various morphologies of the



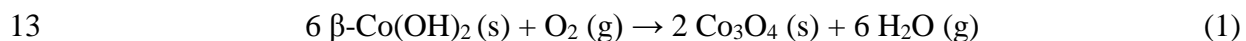
1 nanostructures can be tailored from nanoplates to nanowires by tuning the concentrations  
2 of  $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ , and  $\text{NH}_4\text{NO}_3$ .

3

4 The effect of reaction temperature on the morphology of  $\text{Co}_3\text{O}_4$  nanostructures is shown  
5 in Figure 3. In Fig. 3a (Sample 9), nanowires and several leaf-like crystals with diameters  
6 of 3–6  $\mu\text{m}$  (measured in the middle of the leaf-like crystal) and lengths of approximately  
7 16  $\mu\text{m}$  were present. The surface of the leaf-like crystal was smooth and flat. Figure 3b  
8 (Sample 3) clearly shows that  $\text{Co}_3\text{O}_4$  nanowires were uniformly covered with Ni foam,  
9 which grows densely and vertically from the substrate. The nanowires were uniform, with  
10 diameters of 500–900 nm and lengths of approximately 17  $\mu\text{m}$ . In Fig. 3c (Sample 10),  
11 some of the nanowires grew bigger and longer, and a few of nanowires integrated into a  
12 bigger one. The coexistence of leaf-like crystals and nanowires suggests that the reaction  
13 process was not homogeneous when the temperature was 70° C. We do not understand  
14 the formation mechanism of the leaf-like crystal; however, we propose that this can be  
15 caused by the rapid gathering rate of local  $\text{Co}(\text{II})$  ions. The reason for the enlargement of  
16 nanowires when the temperature was set at 100° C might be the rapid mass transfer,  
17 which led to a fast deposit of  $\text{Co}(\text{II})$  ions on the nuclei. It could also be due to the  
18 increasing number of high-energy sites on the surface of nanowires, which led to the  
19 growth of nanocrystals among the as-prepared nanowires, thereby causing single  
20 nanowires to merge. The results suggest that temperature is a key factor in controlling the  
21 morphology of the nanowires. Well-ordered nanowire arrays were formed at the reaction  
22 temperature of 90° C.

23

1 To summarize the above discussions on the growth of  $\text{Co}_3\text{O}_4$  nanowire arrays, various  
2 sizes of nanowires synthesized at different reaction conditions are shown in Table 1. The  
3 results suggest that the proper reaction condition for preparation of well-ordered  
4 nanowire arrays (Sample 3) were achieved as follows: a reaction time of 12 h, moderate  
5 concentration, and a temperature of  $90^\circ\text{C}$ . Figure 4 shows the XRD patterns of the  
6 samples prepared under this reaction condition. The phase of Ni was found in the pattern  
7 because of the Ni foam substrate. The XRD pattern of non-calcined nanowires contained  
8 the combined phases of brucite  $\beta\text{-Co(OH)}_2$  and spinel  $\text{Co}_3\text{O}_4$ . Some  $\text{Co(II)}$  ions were  
9 oxidized to  $\text{Co(III)}$  ions during the nanowire growth in the solution. The pattern of Fig.  
10 4b matches the pattern of spinel phase  $\text{Co}_3\text{O}_4$  well, indicating that the nanowires were  
11  $\text{Co}_3\text{O}_4$  after calcination. The transformation of  $\beta\text{-Co(OH)}_2$  to  $\text{Co}_3\text{O}_4$  was due mainly to the  
12 oxidation of  $\beta\text{-Co(OH)}_2$  during the calcination. The reaction formula was as follows:



14 The TEM images (Fig. 5) show that the non-calcined nanowire was structural compact,  
15 while the calcined nanowire was loose and consisted of irregularly shaped cracks. Some  
16 cracks were formed from the release of water vapor during the calcination (refer to the  
17 reaction formula 1).

18

19 Figure 6a shows current-potential polarization curves of the  $\text{Co}_3\text{O}_4$  nanowire and  
20 nanoparticle electrodes for electrochemical reduction of  $\text{H}_2\text{O}_2$  in 0.4 M  $\text{H}_2\text{O}_2$  and 3.0 M  
21 NaOH solution at scan rate  $5 \text{ mV s}^{-1}$ . The onset potentials of the two electrodes were  
22 quite similar at around  $-0.15 \text{ V}$ . The catalytic activity of  $\text{H}_2\text{O}_2$  electrochemical reduction  
23 is attributed to the redox couple of  $\text{Co(OH)}_2/\text{Co}_3\text{O}_4$ . The current density on the  $\text{Co}_3\text{O}_4$

1 nanowire electrode was higher than that of the  $\text{Co}_3\text{O}_4$  nanoparticle electrode in the tested  
2 potential range. More importantly, the Ni foam supported  $\text{Co}_3\text{O}_4$  nanowire electrode  
3 showed a much lower potential at -0.6 V than that of the  $\text{Co}_3\text{O}_4$  nanoparticle electrode (-  
4 0.35 V). The  $\text{Co}_3\text{O}_4$  nanoparticle electrode delivered current density of  $85.8 \text{ mA cm}^{-2}$  at -  
5 0.35 V, which is comparable to literature [26]. In contrast, the  $\text{Co}_3\text{O}_4$  nanowire electrode  
6 exhibited a higher current density of  $101.8 \text{ mA cm}^{-2}$  at -0.4 V compared to of the  $\text{Co}_3\text{O}_4$   
7 nanoparticle electrode. The high electrocatalytic performance of  $\text{Co}_3\text{O}_4$  nanowires arises  
8 from the unique 1D nanostructures, which provide not only high surface area for  
9 electrochemical reaction but also a short diffusion path for ions. Such binder-free  
10 approach also results in low internal resistance because  $\text{Co}_3\text{O}_4$  nanowires were in direct  
11 contact with the Ni foam substrate. Results clearly indicated that the Ni foam supported  
12  $\text{Co}_3\text{O}_4$  nanowire electrode exhibited superior catalytic activity and mass transport kinetics  
13 for  $\text{H}_2\text{O}_2$  electrochemical reduction than binder approach powdery electrode. Figure 6b  
14 shows the dependence of the catalytic performance of Ni foam supported  $\text{Co}_3\text{O}_4$   
15 nanowire electrode (Sample 3) on various concentration of  $\text{H}_2\text{O}_2$ . The polarization curves  
16 demonstrated that  $\text{H}_2\text{O}_2$  electrochemical reduction occurs at around -0.1 V and the current  
17 density increases with the potential going from -0.1 to -0.8 V. The cathodic peak current  
18 density increased with the increase of  $\text{H}_2\text{O}_2$  concentration from 0.1 to 0.6 M. Significant  
19 small oxygen bubbles were observed on the electrode surface at an  $\text{H}_2\text{O}_2$  concentration  
20 higher than 0.3 M. Currents began to fluctuate slightly when the potential was decreased  
21 from -0.45 to -0.8 V due to the perturbation of oxygen from  $\text{H}_2\text{O}_2$  decomposition.

22

#### 23 **4. Conclusions**

1 Various  $\text{Co}_3\text{O}_4$  nanowires with different morphology and sizes grown on Ni foam were  
2 successfully prepared via a template-free method. The brucite  $\beta\text{-Co}(\text{OH})_2$  was  
3 transformed to spinel  $\text{Co}_3\text{O}_4$  after calcination in air. The release of water vapor caused  
4 some cracks on the surface of the nanowires. Reaction temperature, the concentration of  
5 reactants, and reaction time are key variables that determine the final size and  
6 morphology of the nanowires. The nanowires grew vertically from the surface of the Ni  
7 foam, and both size and uniformity of the nanowires increased with the prolongation of  
8 reaction time. The nanowires synthesized at 12 h presented the most uniform morphology.  
9 The various morphologies of the nanostructures can be tailored from nanoplates to  
10 nanowires by tuning the concentration of reactants. The reaction temperatures lower or  
11 higher than  $90^\circ\text{C}$  were unfavorable to the growth of well-ordered nanowires. The  $\text{Co}_3\text{O}_4$   
12 nanowires were structurally uniform and crystalline and had diameters of approximately  
13 500–900 nm and lengths of up to  $17\ \mu\text{m}$  in the typical reaction condition (Sample 3). The  
14 Ni foam supported  $\text{Co}_3\text{O}_4$  nanowire electrode showed superior catalytic activity and mass  
15 transport property for  $\text{H}_2\text{O}_2$  electrochemical reduction in an alkaline medium than the  
16  $\text{Co}_3\text{O}_4$  nanoparticle electrode.

17

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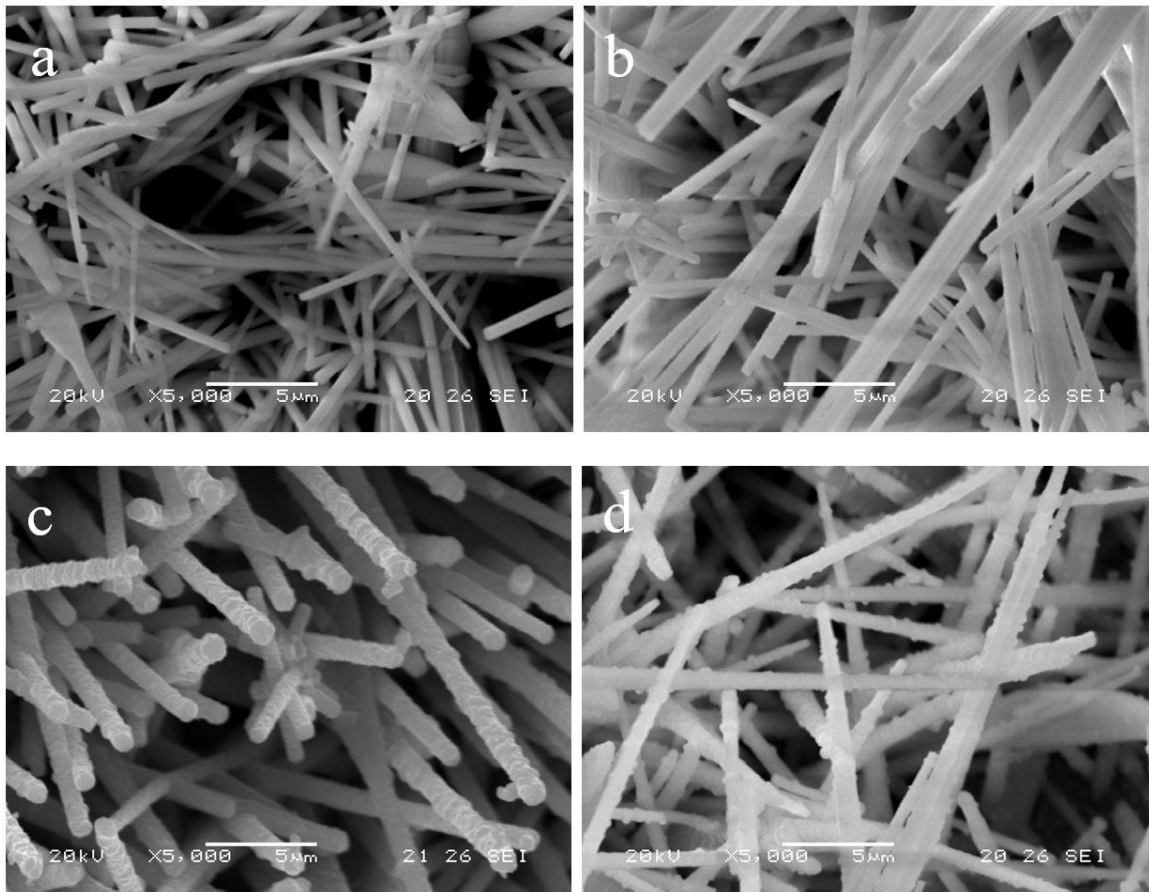
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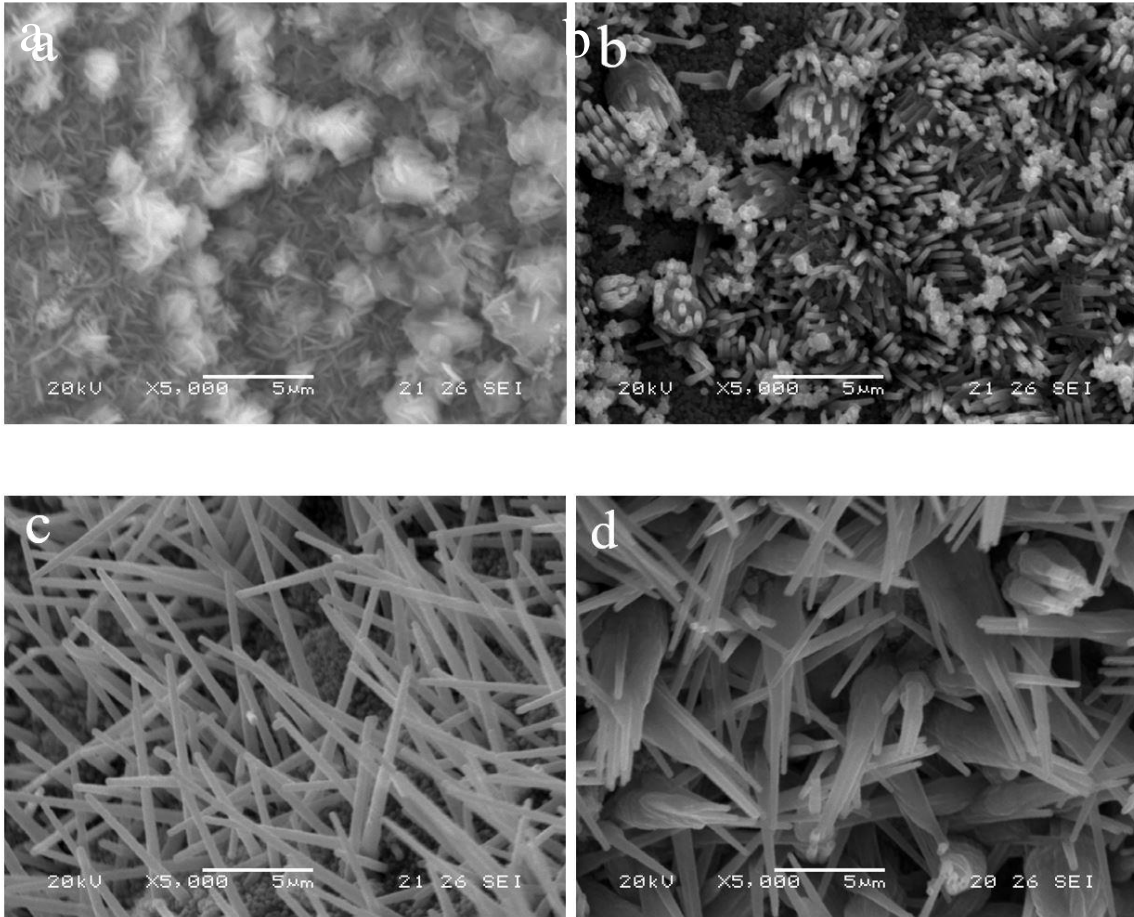
1 Table 1. Various sizes of nanowires synthesized on different reaction conditions

Sample	Time (h)	Concentration (mol/l)			Temperature (°C)	Structure	Nanowire	
		Cobalt nitrate (mol/l)	Ammonium	Ammonia			Diameter (nm)	Length (µm)
			Nitrate (mol/l)	(mol/l)				
1	3	0.2	0.1	6	90	Wire	480~530	10~11
2	6	0.2	0.1	6	90	Wire	520~590	11~14
3	12	0.2	0.1	6	90	Wire	500~900	14~17
4	18	0.2	0.1	6	90	Wire	500~900	15~18
5	12	0.05	0.025	1.5	90	Plate		
6	12	0.1	0.05	3	90	Wire	300~400	2.5~3
7	12	0.15	0.75	4.5	90	Wire	400~550	9~11
8	12	0.25	0.125	7.5	90	Wire	Non-uniform	Non-uniform
9	12	0.2	0.1	6	70	Left like crystal + wire	NA	NA
10	12	0.2	0.1	6	100	Wire	800~6000	20~25

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2 **Fig. 1.** SEM images of  $\text{Co}_3\text{O}_4$  nanowire arrays grown at different times: **a** 3 h (Sample 1),  
3 **b** 6 h (Sample 2), **c** 12 h (Sample 3), **d** 18 h (Sample 4)  
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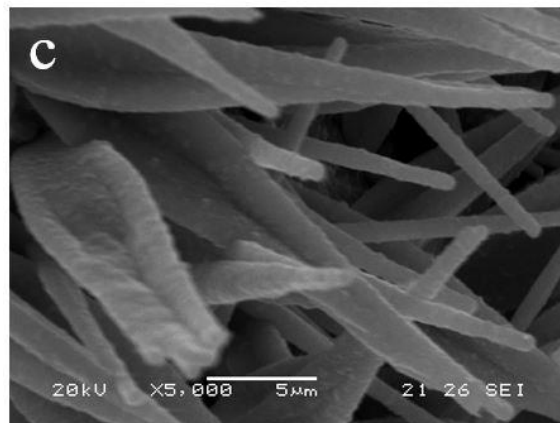
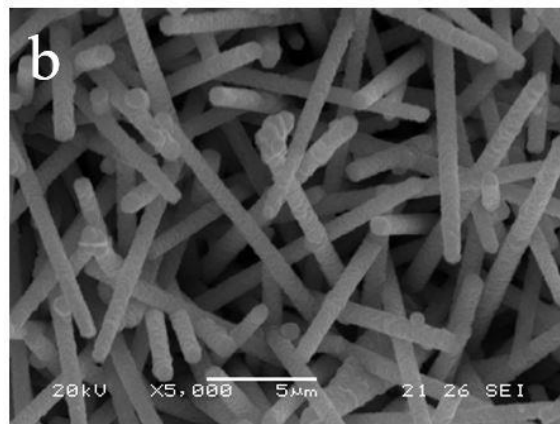
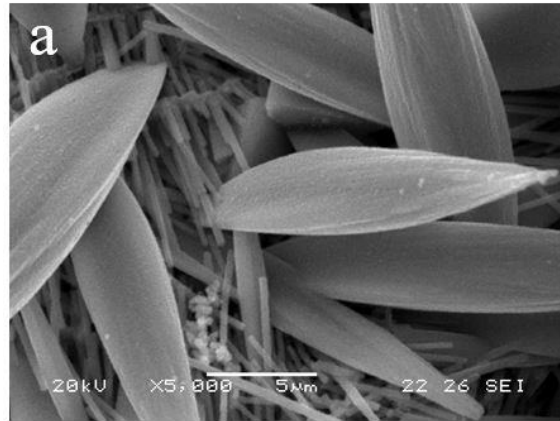


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2 **Fig. 2.** SEM images of the nanoparticles or nanowires synthesized with different  
3 precursor concentrations: **a** Sample 5, **b** Sample 6, **c** Sample 7, **d** Sample 8

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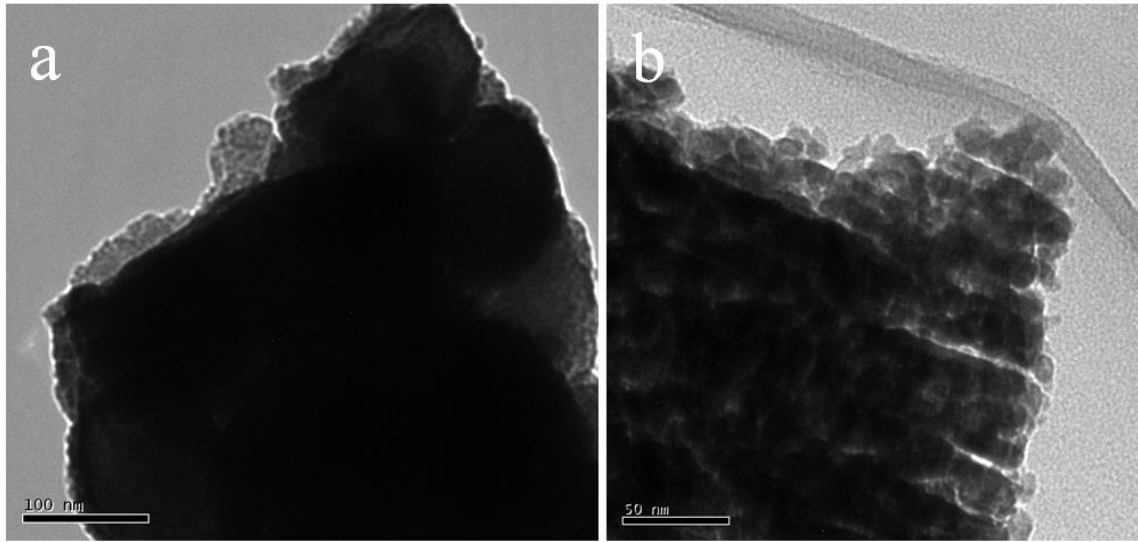
2 **Fig. 3.** SEM images of nanowires or other structures synthesized at different temperatures:

3 **a** 70° C (Sample 9), **b** 90° C (Sample 3), **c** 100° C (Sample 10)

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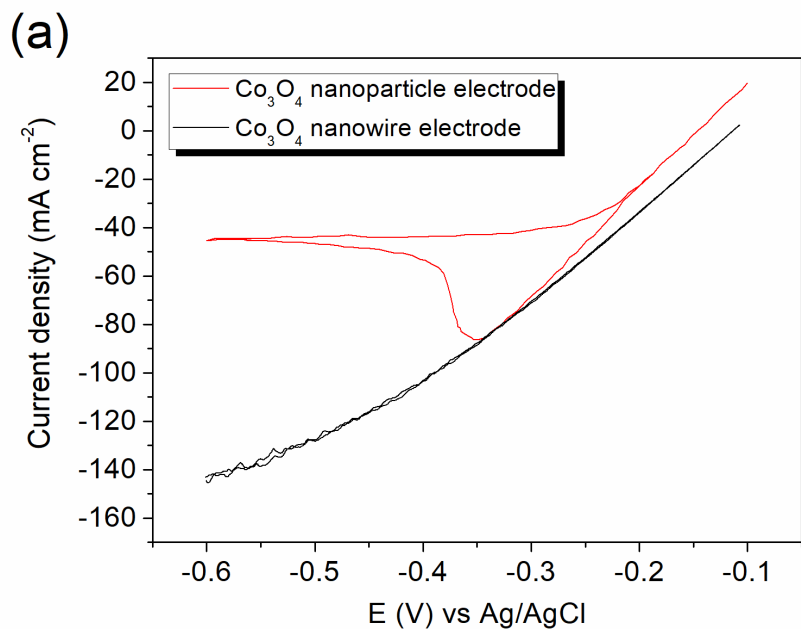
5 **Fig. 5.** TEM images of the nanowires (Sample 3): **a** non-calcined, **b** calcined

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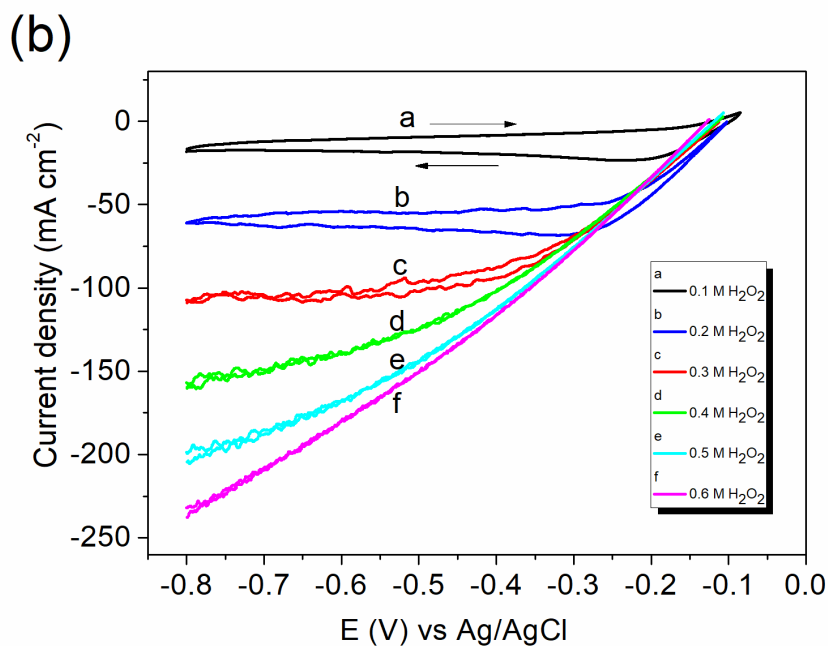
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3 **Fig. 6.** Current-potential polarization curves for  $\text{H}_2\text{O}_2$  electrochemical reduction: **a**  $\text{Co}_3\text{O}_4$   
 4 nanoparticle and nanowire electrodes with electrolyte: 3.0 M NaOH and 0.4 M  $\text{H}_2\text{O}_2$  at  
 5 scan rate  $5 \text{ mV s}^{-1}$ , **b**  $\text{Co}_3\text{O}_4$  nanowires electrode with electrolyte: 3.0 M NaOH and  
 6 different concentrations of  $\text{H}_2\text{O}_2$  at scan rate  $5 \text{ mV s}^{-1}$ .