

Effect of Anodization Duration in the TiO₂ Nanotubes Formation on Ti Foil and Photoelectrochemical Properties of TiO₂ Nanotubes

Asmaa Kadim Ayal*

Department of Chemistry, College of Science for Women, University of Baghdad, Baghdad, IRAQ

*email: asmaakaa_chem@csw.uobaghdad.edu.iq

Article Info

Received
04/10/2018

Accepted
29/10/2018

Published
10/03/2019

Abstract

In this work, the effect of anodizing duration on the morphology and photoelectrochemical properties of TiO₂ nanotubes arrays (NTAs) has been investigated. The samples were characterized by X-ray diffraction (XRD) and energy dispersive X-ray (EDX) to characterize their crystalline structure and composition. Surface morphological and their dimensional variation was examined by field emission scanning electron microscopy (FESEM). The anodizing duration played a significant role in the formation of TiO₂ nanotubes arrays. Moreover, the photoelectrochemical properties (PEC) were studied through photocurrent measurements. Optimum anodizing duration of 60 min at 40 V exhibited maximum photocurrent of 0.03 mA cm⁻² under illumination of halogen light.

Keywords: Anodization duration, TiO₂ nanotube, Photoelectrochemical.

الخلاصة

في هذا العمل، تم التحقق من تأثير مدة الأنودة على المورفولوجيا والخصائص الكهروكيميائية الضوئية لصفائف الأنابيب النانوية (TiO₂ NTAs). شخصت العينات بحيود الأشعة السينية (XRD) والأشعة السينية المشتتة للطاقة (EDX) لتوصيف تركيبها البلوري. تم تشخيص الأشكال السطحية وأبعادها بواسطة المجهر الإلكتروني الماسح (FESEM). لعبت مدة الأنودة دورًا مهمًا في تشكيل صفائف أنابيب النانو TiO₂. علاوة على ذلك، تمت دراسة خواص الكهروكيميائية الضوئية (PEC) من خلال قياسات التيار الناتج عن الضوء. أظهرت مدة الأنودة المثلى خلال 60 دقيقة وفي 40 فولت أقصى تيار ضوئي يبلغ 0.03 مللي أمبير سم⁻² تحت إضاءة ضوء الهالوجين.

Introduction

Photoelectrochemical (PEC) cells based on several metal oxides such as CuO₂, Fe₂O₃, ZnO, and TiO₂ are commonly investigated [1] [2] [3] [4]. Self-organized TiO₂ nanotube arrays (NTAs) have been regarded as potential nanodevices for a photoelectrochemical cell [5], sensor [6], and photocatalysis [7][8], due to their large internal surface area, high adaptability, exceptional electron percolation for a vectorial charge transfer between the interface surfaces, and uniformly stable structure [9][10]. Furthermore, the tubular symmetries with one-dimensional nanostructure have a lower recombination of electron-hole pairs and higher photocurrent conversion efficiency [11]. In recent years, many researchers have paid their attention to

promoting new methods for fabrication of TiO₂ NTAs, such as hydrothermal syntheses [12], template method [13], and anodization [14]. The chemical dissolution rates and electrochemical oxidization of TiO₂ were the keys to produce TiO₂ NTAs by anodization technique. The thin film of TiO₂ was formed on the titanium surface at the beginning of anodization. The small pits could be shown on the surface of the TiO₂ layer after the localized dissolution of TiO₂ via fluorine ions. These small pits act as pore-forming centers. The electric field at the bottom of the pores was increased to improve electrochemical oxidization and chemical dissolution rates of TiO₂ to form TiO₂ NTAs structure. A dynamic balance between chemical dissolution and electrochemical oxidization leads to length of

TiO₂ NTAs stays constant [15]. Zwilling *et al.* fabricated TiO₂ NTAs in chromic acid solution without and with hydrofluoric acid addition by anodization of titanium [16]. Grimes *et al.* produced the highly ordered and uniform TiO₂ NTAs by anodic oxidation of a pure titanium foil in an aqueous solution containing HF [14]. Thenceforth, a variation of electrolytes was being studied to check the probability of producing TiO₂ NTAs with controllable dimensions such as KF/NaF [17], NH₄F/H₃PO₄ [18], polar organic electrolyte [19] [20] and H₂SO₄/HF [21]. Many studies suggested the electrochemical anodization and electrolyte composition condition play a necessary function in influencing the structure and formation of TiO₂ NTAs film. Therefore, in this study, we display the results of an experimental investigation of titanium anodization in NH₄F dissolved in anhydrous ethylene glycol especially the influence of anodization duration on the geometrical aspect and morphology of resulting TiO₂ NTAs and its photocurrent response.

Materials and Methods

Preparation titania nanotube arrays (TiO₂ NTA)

Sheets of Ti foil (thickness 0.127 mm, 99.7% purity) were first cut into pieces of 2 x 1 cm². Then, the pieces of Ti foil were chemical decreasing by ultra-sonication for 15 minutes in acetone, isopropanol and deionized water (DI) respectively. Next, they followed by etching in 6 M HNO₃ to form a smooth surface. Anodization technique on Ti foil was achieved in a dual-electrode cell with the high-density graphite as the counter electrode while Ti foil acts as the working electrode. The distance between two electrodes was preserve at 2 cm. The two electrodes were connected to a power supply and they immersed in electrolyte consisted of 95 ml of anhydrous Ethylene Glycol, 5ml of DI water, and 0.5g of NH₄F. Anodization technique was executed by applying a 40 voltage with different anodization duration (1, 15, 30, 60, and 120) minutes to investigate the effect of anodization duration in the formation of TiO₂ NTAs. As-prepared samples were rinsed with DI water.

The amorphous samples were converted to anatase at 500°C in the air atmosphere (heating rate: 2 °C/min, annealed time: 2 h).

Material characterizations of TiO₂ NTAs

Crystal phases and the morphology of the synthesized TiO₂ NTAs photoelectrodes were analyzed using X-ray diffractometry (Panalytical X, Pert Pro MPD diffractometer by using CuK α radiation, $k = 1.5406 \text{ \AA}$) and field emission scanning electron microscopy (FESEM, JOEL JSM-7600F, Japan) respectively. The elemental analysis was studied using the energy dispersive X-ray (EDX) spectrometers. While the photocurrent measurements of samples were carried out with an (Autolab PGSTAT204/ FRA32M module) potentiostat, with a TiO₂ NTAs as the working electrode (WE), Ag/AgCl as the reference electrode (RE), and Pt wire as the counter electrode (CE).

Results and Discussion

Morphological and structural of TiO₂ NTAs

The diameter of tube plays the most significant factor in determining the performance of the material. As shown in Table 1 and the FESEM images in Figure 1 (b, c, d, e, and f) the tube diameter of the TiO₂ samples varied with anodization duration used. The tube diameter of the samples was analyzed using image analysis software (Image J). FESEM images at chosen time period are shown in Figure 1. The bare Ti plate showed a flat and smooth surface (Figure 1(a)) and in the initial step of anodization, an only a porous layer was formed within 1 minute as can be seen in Figure 1 (b). Over 15 minutes of anodization, the porous layer converted into a tube-like surface morphology with several precipitates (Figure 1(c)). At increasing the duration of anodization to 30 minutes, reduced surface precipitates with well-separated tubes were obtained as shown in Figure 1 (d)). After 60 minutes, the surface was quite filled with self-organized and well-ordered TiO₂ NTAs (Figure 1(e)). The tube diameter range becomes larger by increasing the anodizing time to 120 minutes, as shown in Figure 1(f), while the top of the

TiO₂ NTAs is gradually broken due to over-dissolution of the top of the tubes [22].

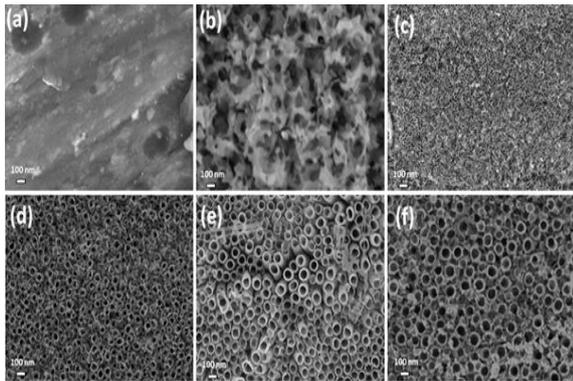


Figure 1: FESEM images showing the (a) Ti foil and different stages of TiO₂ NTAs film formation at 40 V in NH₄F/EG/H₂O solution for (b) 1 min (c) 15 min (d) 30 min (e) 60 min and (f) 120 min

Table 1: diameter range of TiO₂ NTAs prepared at different anodization duration in NH₄F/EG/H₂O solution

| Time (min) | Diameter (nm) |
|------------|---------------|
| 1 | - |
| 15 | 5-10 |
| 30 | 16-42 |
| 60 | 60-90 |
| 120 | 72- 108 |

Figure 2 shows the XRD patterns of Ti foil and TiO₂ NTAs prepared at various anodization duration, only peaks for anatase phase are found (JCPDS: 21-1272) at 2θ (25.8°, 37.6°, 48.05°, 54.0° and 55.0°) corresponding to [101], [004], [200], [105], and [211] respectively. The extra peaks that at 35.45°, 38.8°, 40.5°, and 53.4° was produced from titanium substrate. It is also observed that the [101] reflections presented the highest intensity as a contrast to another anatase peaks for all samples that confirm which this plane is the best orientation for the nanotubes. Moreover, it is clearly seen that the intensity of the peak [101] increase with increasing anodization duration to 60 minutes due to the enhancement in the crystallinity of the TiO₂ NTAs. Furthermore, the intensity of the peak (101) decreases when anodization duration was 120 minutes (Figure 2 (f)) that was ascribed to the non-homogenous TiO₂ NTAs structure.

Figure 3 shows the EDX spectrum that demonstrated the presence of titanium and oxygen elements. The ratio of Ti to O element is about 1:2 thereby confirmed the formation of stoichiometry TiO₂ NTAs.

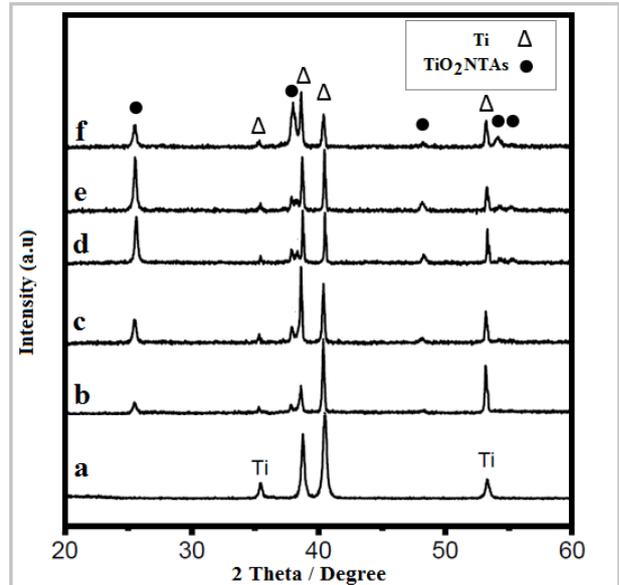


Figure 1: XRD patterns showing the (a) Ti foil and different stages of TiO₂ NTAs film formation at 40 V in NH₄F/EG/H₂O solution for (b) 1 min (c) 15 min (d) 30 min (e) 60 min and (f) 120 min.

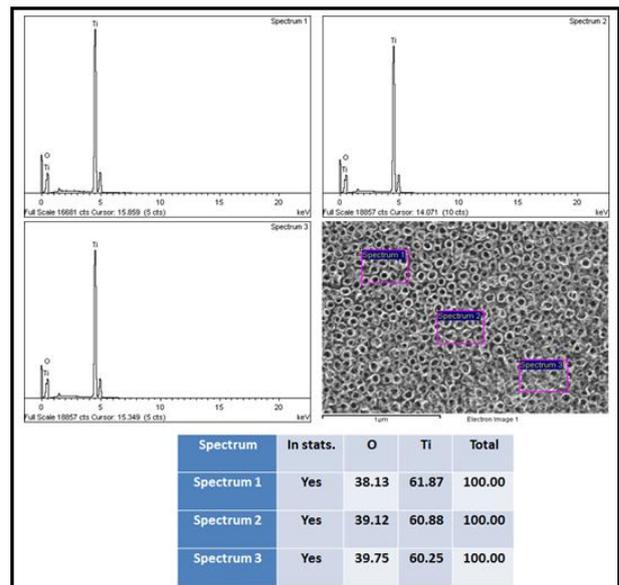


Figure 3: EDX spectra of TiO₂ NTAs prepared at 60 min anodization duration.

Photoelectrochemical cell performance of TiO₂ NTAs:

A comparison between the photoelectrochemical cell (PEC) performances of the TiO₂ NTAs was conducted in a three-electrode PEC cell with intermittent illumination. Figure 4 shows the current-voltage (I–V) curves that obtained from the TiO₂ NTAs photoelectrode which was synthesized at different anodization duration. The photocurrent response increases when anodization duration increased from 1 to 60 minutes, while the photocurrent response decreased when the anodization duration reached to 120 minutes. This result means that photogenerated electrons have been transferred easily from TiO₂ NTAs to the counter electrode under illumination by the external circuit when prepared the sample at 60 minutes anodization duration.

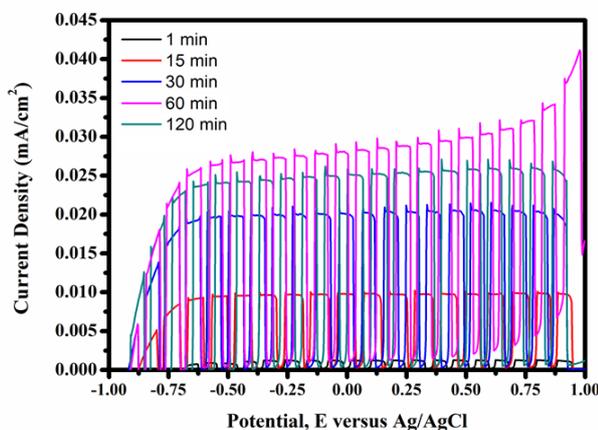


Figure 4: photocurrent responses of TiO₂ NTAs prepared at different anodization duration

Conclusion

In summary, anodization technique was successfully applied to obtain well-ordered and uniform TiO₂ NTAs films. The anatase phase of the TiO₂ NTAs occurred under the annealing temperature of 500 °C. This study exposes that optimal anodization duration of 60 minutes is required to get maximum the photoresponse of TiO₂ NTAs. The morphology of the TiO₂ NTAs is very significant and obviously, a variation in behaviour once the change from a porous layer to well-defined TiO₂ NTAs is achieved. Furthermore, extended anodization duration to 120 minutes at 40V causes some

damage to TiO₂ NTAs and their photocurrent decreases.

Acknowledgment

Special thanks are extended to Department of Chemistry and Department of Physics, Faculty of Science, Universiti Putra Malaysia, and Microscopy Unit, Institute of Bioscience, Universiti Putra Malaysia.

References

- [1] T. G. Kim, H. B. Oh, H. Ryu, and W. J. Lee, "The study of post annealing effect on Cu₂O thin-films by electrochemical deposition for photoelectrochemical applications," *J Alloys Compd*, vol. 612, pp. 74–79, 2014.
- [2] M. C. Huang, W. S. Chang, J. C. Lin, Y. H. Chang, and C. C. Wu, "Magnetron sputtering process of carbon-doped α -Fe₂O₃ thin films for photoelectrochemical water splitting," *J Alloys Compd*, vol. 636, pp. 176–182, 2015.
- [3] A. M. Holi, Z. Zainal, Z. A. Talib, H.-N. Lim, C.-C. Yap, S.-K. Chang, and A. K. Ayal, "Enhanced photoelectrochemical performance of ZnO nanorod arrays decorated with CdS shell and Ag₂S quantum dots," *Superlattices Microstruct*, vol. 103, pp. 295–303, 2017.
- [4] A. K. Ayal, Z. Zainal, H.-N. Lim, Z. A. Talib, Y.-C. Lim, S.-K. Chang, and A. M. Holi, "Photocurrent enhancement of heat treated CdSe-sensitized titania nanotube photoelectrode," *Opt Quantum Electron*, vol. 49, no. 4, pp. 1–11, 2017.
- [5] A. Kadim, Z. Zainal, H. Ngee, Z. Abidin, Y. Lim, S. Chang, and A. Mebdir, "Fabrication of CdSe nanoparticles sensitized TiO₂ nanotube arrays via pulse electrodeposition for photoelectrochemical application," *Mater Res Bull*, vol. 106, no. December 2017, pp. 257–262, 2018.
- [6] P. Roy, S. Berger, and P. Schmuki, "TiO₂ nanotubes: Synthesis and applications," *Angew Chemie - Int Ed*, vol. 50, no. 13, pp. 2904–2939, 2011.
- [7] W. Wang, F. Li, D. Zhang, D. Y. C. Leung, and G. Li, "Applied Surface Science Photoelectrocatalytic hydrogen generation and simultaneous degradation of organic pollutant via CdSe / TiO₂ nanotube arrays," *Appl Surf Sci*, vol. 362, pp. 490–497, 2016.
- [8] S. G. Ghugal, S. S. Umare, and R. Sasikala, "Enhanced photocatalytic activity of TiO₂ assisted by Nb, N and S multidopants," *Mater Res Bull*, vol. 61, pp. 298–305, 2014.
- [9] K. Shankar, J. I. Basham, N. K. Allam, O. K. Varghese, G. K. Mor, X. Feng, M. Paulose, J. a Seabold, K. Choi, and C. a Grimes, "Recent Advances in the Use of TiO₂ Nanotube and

- Nanowire Arrays for Oxidative photoelectrochemistry,” *J Phys Chem C*, vol. 113, no. 16, pp. 6327–6359, 2009.
- [10] O. K. Varghese, M. Paulose, T. J. LaTempa, and C. A. Grimes, “High-rate solar photocatalytic conversion of CO₂ and water vapor to hydrocarbon fuels,” *Nano Lett*, vol. 9, no. 2, pp. 731–737, 2009.
- [11] J. M. Macák, H. Tsuchiya, A. Ghicov, and P. Schmuki, “Dye-sensitized anodic TiO₂ nanotubes,” *Electrochem commun*, vol. 7, no. 11, pp. 1133–1137, 2005.
- [12] T. Kasuga, M. Hiramatsu, A. Hoson, T. Sekino, and K. Niihara, “Formation of Titanium Oxide Nanotube,” *Langmuir*, vol. 14, no. 12, pp. 3160–3163, 1998.
- [13] P. Hoyer, “Formation of a Titanium Dioxide Nanotube Array,” *Langmuir*, vol. 12, no. 6, pp. 1411–1413, 1996.
- [14] D. Gong, C. a. Grimes, O. K. Varghese, W. Hu, R. S. Singh, Z. Chen, and E. C. Dickey, “Titanium oxide nanotube arrays prepared by anodic oxidation,” *J Mater Res*, vol. 16, no. 12, pp. 3331–3334, 2001.
- [15] G. K. Mor, O. K. Varghese, M. Paulose, K. Shankar, and C. a. Grimes, “A review on highly ordered, vertically oriented TiO₂ nanotube arrays: Fabrication, material properties, and solar energy applications,” *Sol Energy Mater Sol Cells*, vol. 90, no. 14, pp. 2011–2075, 2006.
- [16] V. Zwillling, D. David, M. Y. Perrin, and M. Aucouturier, “Structure and Physicochemistry of Anodic Oxide Films on Titanium and TA6V Alloy,” *Surf. Interface Anal.*, vol. 637, no. October 1998, pp. 629–637, 1999.
- [17] Q. Cai, “The effect of electrolyte composition on the fabrication of self-organized titanium oxide nanotube arrays by anodic oxidation,” *J Mater Res*, vol. 20, pp. 230–236, 2005.
- [18] M. S. Su, F. Alamgir, P. Scardi, and A. Ahmad, “Morphological Studies of Vertical Arrays TiO₂ Nanotubes by Electrochemical Anodization Technique for Dye Sensitized Solar Cell Application,” *AIP Conf Proc*, vol. 1571, no. 2013, pp. 835–842, 2013.
- [19] H. E. Prakasam, K. Shankar, M. Paulose, O. K. Varghese, and C. A. Grimes, “ARTICLES A New Benchmark for TiO₂ Nanotube Array Growth by Anodization,” *J Phys Chem C*, vol. 111, pp. 7235–7241, 2007.
- [20] M. Paulose, K. Shankar, S. Yoriya, H. E. Prakasam, O. K. Varghese, G. K. Mor, T. J. LaTempa, A. Fitzgerald, and C. a Grimes, “Anodic growth of highly ordered TiO₂ nanotube arrays to 134 microm in length.,” *J Phys Chem B*, vol. 110, no. 33, pp. 16179–16184, 2006.
- [21] X. Chen, X. Chen, J. Tang, and S. Chen, “Energy Procedia Preparation of Self-organized Titania Nanotubes Electrode and Its Electrochemical Properties,” *Energy Procedia*, vol. 16, pp. 1206–1210, 2012.
- [22] D. Regonini and F. J. Clemens, “Anodized TiO₂ Nanotubes : Effect of anodizing time on film length, morphology and photoelectrochemical properties,” *Mater Lett*, pp. 1–5, 2014.