We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Synthesis of Titanium Dioxide Nanorod Arrays Using a Facile Aqueous Sol-Gel Route for Ultraviolet Photosensor Applications

Marmeezee Mohd. Yusoff,
Mohamad Hafiz Mamat and
Mohamad Rusop Mahmood

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.68460>

Abstract

In this chapter, we review the state of the art of aqueous sol-gel route for ultraviolet (UV) photosensor applications based on the nanostructured TiO_2 . The performance of UV photosensor is associated with the high surface-to-volume ratio, porosity, surface defects, light trapping, and the intensity of the UV radiation. One-dimensional (1D) growth of TiO_2 nanorod arrays (TNAs) offers an enhance charge carrier mobility to overcome the photocurrent loss due to the existence of multiple grain boundaries in granular-like and porous nanostructures. Photoelectrochemical cell (PEC)-based device structure is preferred in TNA-based UV photosensor due to its low cost, facile fabrication process, high contact area, low recombination of the excitonic charge carriers, high photocurrent gain, and fast response and recovery times. It also could work in applied bias mode, as well as in “self-powered” mode. Our study has introduced a new one-step method to deposit a thin film TNA on an FTO-coated glass substrate at low temperature and a rapid process using a facile glass container. The fabricated PEC-based UV photosensor using the deposited TNAs has successfully shown its potential in the application of UV photosensor.

Keywords: TiO_2 , nanorod arrays, UV photosensor

1. Introduction

Titanium dioxide (TiO_2) nanostructures emerged as one of promising materials for electronic device applications such as diodes, transistors, memristors, sensors, and solar cells. TiO_2 with numerous nanostructures yield a unique, expedient, and novel size and shape-dependent

was 2.94 mA/W under UV irradiation and 6.92 mA/W under 365 nm UV light. The work suggested that TiO_2 content was in correlation with the photogenerated current density, which is related to the deviation of the size of the interface between the two components that attributed to the agglomeration of TiO_2 nanoparticles. It was also mentioned that the high crystallinity of TiO_2 nanocrystals and a small size distribution were very significant for chemicophysical property, which enhanced the electron-transporting mechanism in the fabricated device.

One study by Vigil et al. examined the trend in a sealed two-electrode photoelectrochemical cell (PEC) using a double-layer of nanocrystalline TiO_2 [8]. A double layer of TiO_2 (**Figure 1**) was introduced through a “doctor-blading” technique for a mesoporous TiO_2 ($\sim 5\ \mu\text{m}$ thickness) layer on top, while the bottom TiO_2 film ($\sim 100\ \text{nm}$ thickness) obtained via microwave-assisted chemical bath deposition (MW-CBD) on transparent conducting oxide (TCO)-coated glass as contact electrodes. The sol-gel was consisted of the aqueous solutions of $(\text{NH}_4)_2\text{TiF}_6$ solution and H_3BO_3 . The fabricated device showed an I - V curve of a junction diode characteristic. The measured short circuit photogenerated current values was 0.3–0.4 mA under UV radiation ($\lambda = 340\ \text{nm}$) and linearly dependent on radiation intensity. The chapter suggested that the mesoporous structure with nanocrystallites (20–30 nm in size) allowed the penetration of electrolyte, which rapidly captured the holes through the iodide ions in the electrolyte from the high surface area of TiO_2 during the irradiation and thus hindered the recombination of electron-hole pairs for longer diffusion of electrons to TCO anode contact. They also proposed that the existence of the dense thin film deposited on top of the TCO inhibited the recombination of electrons in the TCO with species in the electrolyte.

Figure 1. Schematic of UV photosensor based on photoelectrochemical cell (PEC) using a double-layer of nanocrystalline TiO_2 [8].

Another study of two-electrode PEC-based self-powered UV photosensor using a nanocrystalline TiO_2 was reported by Li et al. [9]. The performance of the fabricated self-powered photosensor was described to be isolated from the surrounding environment through the unique sandwich structure of PEC. Nanocrystalline TiO_2 was deposited through a spin-coating technique for a mesoporous structure (450 nm thickness) on an FTO-coated glass substrate as a contact electrode and followed by annealing at 500°C in air for 2 hours. The sol-gel was consisted of tetrabutyltitanate, acetic acid, ethanol, poly(vinyl pyrrolidone) (PVP), *N,N*-dimethylformamide (DMF), and tri-ethanolamine (TEOA). The measured short circuit photogenerated current values was 54 mA/cm^2 under UV radiation ($\lambda = 330 \text{ nm}$, 150 mW/cm^2) at 0 V bias and linearly dependent on radiation intensity.

Xiang et al. proposed a porous and dense nanocrystalline TiO_2 films grown on the FTO-coated glass substrate using a spin-coating technique from nanosized TiO_2 particles synthesized via hydrothermal method for vertical geometry UV photosensor [10]. Both porous and dense films were prepared at the same thickness, and the porous film was consisted of particles with an average size of 30 nm. The sol-gel was consisted of titanium isopropoxide, acetic acid, DI water, and HNO_3 . Polyethylene glycol was added in the sol-gel to produce the porous film. They suggested that the response time of vertical geometry photosensor was faster than the lateral geometry photosensor for MSM-based device. The I - V characteristic of the porous film showed better rectifying behavior than that of the dense film. The photoresponsivity measured in photovoltage of the porous film was higher than that of the dense film under the 248-nm laser pulse irradiation due to light-scattering effects, which improved the light harvesting efficiencies in the deposited film. However, the response time of the porous film was slightly longer than that of the dense film in correlation with higher defect density in the porous film. They also suggested that the dislocation direction, which was parallel to the vertical geometry of photosensor, reduced the response time than that of the lateral geometry due to the reduction of mobility fluctuation of the charge carriers.

Another report of MSM-based TiO_2 UV photosensor on the LaAlO_3 substrate was introduced by Lv et al. using a sol-gel spin coating technique with Pt-interdigitated electrodes on the top of TiO_2 film [11]. The sol-gel was consisted of tetrabutyltitanate ($\text{Ti}(\text{OC}_4\text{H}_9)_4$), ethanol ($\text{C}_2\text{H}_5\text{OH}$), CH_3COOH , acetylacetone, and DI water. A high responsivity of 31.7 A/W was achieved under the UV radiation (260 nm, $26.5 \text{ }\mu\text{W/cm}^2$) at 5 V bias. Very low dark current was reported at 50 pA, and the ratio of the photogenerated current to dark current reached 5 orders of magnitude. The device also showed fast response and recovery at the ON and OFF states, respectively. They suggested that the low dark current achieved was due to increase of Schottky barrier height between Pt and TiO_2 , which attributed to a wide depletion region. The formation of a heterojunction and depletion region at the interface of $\text{TiO}_2/\text{LaAlO}_3$, and the formation of reverse-biased junction from one of the two back-to-back Schottky junctions at Pt/ TiO_2 interfaces were also attributed to the reduction of the dark current. The decrease of rise time was also due to the depletion region at the interface of $\text{TiO}_2/\text{LaAlO}_3$, where a large number of electrons from the electron-hole pairs generated and separated during the irradiation of UV were drifted toward the anode electrode. Meanwhile, the significant decrease of fall time during the OFF state was due to the rapid recombination of the balanced electrons with the holes in the depletion region at the interface of $\text{TiO}_2/\text{LaAlO}_3$.

Selman et al. developed a p-n heterojunction-based UV photosensor consisted of n-type TiO_2 on the p-type silicon substrate [12]. The work involved a deposition of TiO_2 seed layer on the p-type (1 1 1)-oriented silicon wafer via radio-frequency (RF) magnetron sputtering. Chemical bath deposition (CBD) technique was performed to grow rutile TiO_2 nanorods (NRs) with an average diameter of 30–35 nm and an average length of 85 nm on the seed layer of silicon substrate. The sol-gel was consisted of titanium (III) chloride (TiCl_3), urea (NH_2CONH_2), and DI water. A Pt electrode (~100 nm thickness) was deposited as a front contact on the TiO_2 NRs via RF magnetron sputtering. Their study stated that the responsivity of the device was significantly improved in correlation with bias voltage, and the responsivity achieved were 164.8, 377.0, and 538.5 A/W at 3, 5, and 7 V bias, respectively, under the UV radiation (405 nm, 0.22 mW/cm²). High responsivity was due to high density and larger and rougher surface area of the deposited TiO_2 NRs, and good formation of p-n junction in the TiO_2 NRs/p-Si(1 1 1) interface. In addition, high photogenerated current achieved was due to the high crystallinity structure of the deposited rutile TiO_2 , with reduced grain boundaries and defects on the structure that created electron trap to hinder the transportation of the charge carriers. Moreover, high aspect ratio also increased the photogenerated current due to oxygen desorption at the surface of TiO_2 NRs.

Another interesting study that utilized the MSM-based UV photosensor with a NH_4^+ modified TiO_2 film and interdigitated Au electrodes on quartz substrates was reported by Liu et al. [13]. TiO_2 was deposited using a sol-gel spin coating technique and subsequently immersed in ammonium sulfide $[(\text{NH}_4)_2\text{S}]$ solution to generate NH_4^+ modified TiO_2 films. The sol-gel consisted of tetrabutyltitanate ($\text{Ti}(\text{OC}_4\text{H}_9)_4$), ethanol ($\text{C}_2\text{H}_5\text{OH}$), acetic acid (CH_3COOH), acetylacetone, and DI water. A high photogenerated current of 84.93 μA and responsivity of 361.07 A/W was achieved under the UV radiation (300 nm, 61.9 $\mu\text{W}/\text{cm}^2$) at 5 V bias. Surface modification of TiO_2 film also showed the decrease of rise time to 366.9 ms and dark current to 88.8 pA than that of the TiO_2 without the surface modification. They found that the decrease in the Schottky barrier height (SBH) between TiO_2 and Au was due to the generation of dipole between NH_4^+ and exposed oxygen ions, replacing the H^+ on the deposited TiO_2 surface, which increased the performance of the device.

Yang et al. fabricated an MSM-based UV photosensor with two-dimensional (2D) TiO_2 nanosheets (TiO_2NS) deposited on 150 nm thickness of Ag IDT-electrodes on a glass substrate [14]. TiO_2NS was prepared via a sol-gel hydrothermal technique and calcined at different temperatures for 2 hours. The sol-gel was consisted of tetrabutyltitanate (TBOT), HCl, polyethylene oxide-polypropylene oxide-polyethylene oxide ($\text{PEO}_{20}\text{-PPO}_{70}\text{-PEO}_{20}$), ethanol (EtOH), and ethylene glycol (EG). The thickness of deposited TiO_2NS was about 1–7 nm, in correlation with 2–10 stacking layers of the monolayer (0.62 nm thickness). The measured photogenerated current of 69.4 nA was achieved under the UV radiation (3 mW/cm²) at 1 V bias, with ultralow dark current (~2.63 pA) and fast response and recovery times. Low dark current may partly attributed from the boundaries between the nanosheets, which hindered the mobility of the charge carriers.

In previous studies on the TiO_2 -based UV photosensor, the application of nanostructure materials have a lot of advantages over bulk materials, comprising high photogenerated current,

high responsivity, fast response and recovery times, low power consumption, and miniaturization of the device structure. Thus far, a number of studies have highlighted the factors that are associated with the high responsivity of nanostructured devices in correlation with a high surface-to-volume ratio, surface defects, light trapping, charge carriers trapping, and high porosity [4]. The performance of the device was also dependent on the device structure and the detection mechanism of photon through the photogenerated charge carriers. Thus far, several studies have used some instances of UV photosensor based on p-i-n photodiodes, p-n junction, Schottky barrier (SB), and MSM structure, and these types of photosensors required an external bias with potential difference to hinder the recombination of the excitonic charge carriers. Such mechanism for most conventional sensors generally required an external power supply sources from batteries, or additional supplies from the controller systems for instances, which against the concept of miniaturization of future device system and also prominently reduced the independency and mobility of the detection system. Furthermore, energy supply has becoming one of the great challenges for large-scale area applications of the sensors [15]. The techniques to synthesize and deposit the TiO_2 nanostructures on the substrate are also important to be considered in addition to produce a rapid production and low-cost device. Much of the previous research has focused on the synthesization and deposition of granular-like and porous nanocrystalline TiO_2 that contributed to the enlargement of reactive surface area of detecting component. Much of the literature has also emphasized the lifetime of photogenerated charge carriers in conjunction to reduce the recombination rate of electron-hole pairs. The charge carrier's transportation is also relatively important in maximizing the overall photocurrent gain, as the effective charge carrier mobility is desired for high efficiency devices.

3. TiO_2 nanorod arrays (TNAs) and TiO_2 nanowires (TNWs) in UV photosensor

A considerable amount of literature has been studied on controlling the nanostructures of TiO_2 to enhance the responsivity of the UV photosensor. Granular-like and porous nanocrystalline TiO_2 , for instance, provides a high reactive surface area to enhance the detection. However, the granular-like structure has deficiency on charge carrier's mobility in attribution to multiple grain boundaries, which hinder the transportation of charge carriers. Recently, researchers have shown an increased interest in one-dimensional (1-D) nanostructure of TiO_2 nanorod arrays (TNAs) and TiO_2 nanowires (TNWs) for UV photosensor applications due to their unique and excellent characteristics on size and shape, as well as their optical, electrical, and physical and chemical properties. Structures of TNAs and TNWs show high aspect ratio (length/diameter) larger than 1, with outstanding charge carrier's mobilities that are extremely suitable for a UV-sensing device. The size and shape may influence the optical property and give different performance on the photosensing device. Therefore, control over the shape and size depending on the method and experimental parameters used to synthesize the nanorods' structure has been one of the vital and challenging tasks. TNAs or TNWs offer a direct carrier's pathway, which increased the transportation rate and enhanced the performance of photosensor, as well as a photovoltaic type of optoelectronic devices [16, 17].

5. Performance of synthesized TNAs-based UV photosensor

The proposed sol-gel immersion method is used for the development of a one-dimensional growth of uniform and densely array of nanorods structure. TNAs (120 nm diameter, 1.52 μm in length) were successfully synthesized and deposited on the FTO-coated glass substrate, as shown in **Figure 5**. The topography images of AFM (**Figure 6**) exhibited the comparable image structure of the top view as observed using FESEM. The measured root mean square roughness, R_{rms} , and average roughness, R_a , of the synthesized TNAs were approximately 38.52 and 30.37 nm, respectively. In general, the growth of TNAs is basically formed via the chemical reactions throughout the nucleation and growing processes through the hydrolysis of titanium(IV) butoxide in acidic solution. The proposed reaction mechanisms were emphasized on two steps as follows [25, 26]:

where $\text{R} = \text{C}_4\text{H}_9$.

At a regular state, the process of hydrolysis for titanium yields a definite amount of heat and occurs immediately at room temperature. The HCl was used as a stabilizer in the sol-gel to minimize the reaction rate from instantly developing precipitation or aggregation during the preparation stage, in attribution to the presence of free H^+ [27, 28]. At the same time, the 1D growth of TNAs at the preferred [001] direction was due to the presence of Cl^- , which bonded to the (1 1 0) plane and preventing the growth of TiO_2 crystal structure at its direction, to some extent [16, 29].

The crystal clear condition of the prepared sol-gel at room temperature showed the sufficiency of HCl content in the solution. Eq. (1) exhibits the hydrolysis process of titanium, which removes four carbon atoms from the precursor to form titanium hydroxyl and alkoxy group. The presence of H^+ through the addition of HCl as the stabilizer in this equation prevents the hydrolysis rate of titanium. The condensation process in Eq. (2) synthesizes TiO_2 and produces water. In order to produce highly aligned 1D growth of the TNAs from titanium alkoxide in the sol-gel, the ratio of DI water and HCl, and the growth rate through time and temperature need to be tuned and optimized. On heating during the sol-gel immersion process, the growth rate increases in correlation with synthesization and deposition time, which contributes to the

Figure 5. FESEM images of the TNAs at magnifications of (a) 20,000 $\times$ and (b) 70,000 $\times$. (c) Cross-sectional images of the synthesized TNAs.

Figure 6. AFM images of the synthesized TNAs [25].

nucleation of TiO_2 on the seeds of FTO from the substrate. The nucleation of TiO_2 is basically based on the atomic structuring of TiO_6 octahedron as the fundamental unit, which plays an important role in the formation of tetragonal structure of TiO_2 . The arrangement and interconnection of TiO_6 octahedral determine the phase and structure of the synthesized TiO_2 . The rutile phase of TNAs synthesized in our method indicated that the edge sharing of TiO_6 octahedral occurred during the formation of tetragonal structure of TiO_2 .

Figure 7 shows the XRD pattern of the synthesized and deposited TNAs. The rutile peaks of TiO_2 were detected at (1 0 1), (2 1 0), (2 1 1), (3 1 0), (0 0 2), and (1 1 2) planes, and no peaks which indicated the anatase and brookite phases observed in the pattern (JCPDS No.01-072-1148). Intense peaks at (0 0 2) and (1 0 1) planes showed that the 1D growth of TNAs was at the [0 0 1] direction.

Figure 8(a) shows the spectrum of optical absorbance of the synthesized and deposited TNAs on the FTO-coated glass substrate in a range of 200–800 nm. The spectrum exhibits that the intensity of the absorbance is significantly increased below 400-nm wavelength, which is in the UV region. Therefore, the optical characteristic of the deposited TNAs to absorb the UV radiation could be utilized for the application of UV photosensor as predicted. The performance of the developed UV photosensor was measured under 365-nm UV radiation at a bias voltage of 1 V. **Figure 8(b)** exhibits the time-dependent photogenerated current of the developed UV photosensor using the deposited TNAs. The result shows an average increase of 0.1 mA of photogenerated current under UV radiation, which is attributed to the photogenerated electrons through the excitation from the valance band into the conduction band. The rise and fall times are negligible throughout the measurement. Thus, the fabricated UV photosensor from the deposited TNAs facilitates the potential application in a low-power UV detecting device.

The present study was designed to introduce a new one-step method to synthesize and deposit a thin film TNAs on the FTO-coated glass substrate at low temperature and rapid process using the facile glass container for the application of UV photosensor. Although the fabricated UV photosensor has successfully shown its potential application in sensing the UV radiation, more research is required to determine the optimum efficiency of the device, through the variation of synthesization and deposition parameters, composition of electrolytes, composition of sol-gel, device structure, and many more. This research has opened up many opportunities of further investigation.

References

- [1] Pfeifer V, Erhart P, Li S, Rachut K, Morasch J, Brötz J, Reckers P, Mayer T, Rühle S, Zaban A, Mora Seró I, Bisquert J, Jaegermann W, Klein A. Energy band alignment between anatase and rutile TiO₂. *The Journal of Physical Chemistry Letters*. 5 December 2013;**4**:4182–4187
- [2] Xie Y, Wei L, Wei G, Li Q, Wang D, Chen Y, Yan S, Liu G, Mei L, Jiao J. A self-powered UV photodetector based on TiO₂ nanorod arrays. *Nanoscale Research Letters*. 2013;**8**:188
- [3] Cao G, Wang Y. *Nanostructures and Nanomaterials: Synthesis, Properties, and Applications*. 2nd ed. New Jersey: World Scientific; 2011
- [4] Soci C, Zhang A, Bao XY, Kim H, Lo Y, Wang D. Nanowire photodetectors. *Journal of Nanoscience and Nanotechnology*. March 2010;**10**:1430–1449
- [5] Okuya M, Shiozaki K, Horikawa N, Kosugi T, Kumara GRA, Madarász J, Kaneko S, Pokol G. Porous TiO₂ thin films prepared by spray pyrolysis deposition (SPD) technique and their application to UV sensors. *Solid State Ionics*. 2004;**172**:527–531
- [6] Xue H, Kong X, Liu Z, Liu C, Zhou J, Chen W, Ruan S, Xu Q. TiO₂ based metal-semiconductor-metal ultraviolet photodetectors. *Applied Physics Letters*. 2007;**90**:201118
- [7] Han Y, Wu G, Wang M, Chen H. High efficient UV-a photodetectors based on mono-dispersed ligand-capped TiO₂ nanocrystals and polyfluorene hybrids. *Polymer*. 2010;**51**:3736–3743
- [8] Vigil E, Peter LM, Forcade F, Jennings JR, González B, Wang H, Curbelo L, Dunn H. An ultraviolet selective photodetector based on a nanocrystalline TiO₂ photoelectrochemical cell. *Sensors and Actuators A: Physical*. 2011;**171**:87–92
- [9] Li X, Gao C, Duan H, Lu B, Pan X, Xie E. Nanocrystalline TiO₂ film based photoelectrochemical cell as self-powered UV-photodetector. *Nano Energy*. 2012;**1**:640
- [10] Xiang WF, Yang PR, Wang AJ, Zhao K, Ni H, Zhong SX. Vertical geometry ultraviolet photodetectors with high photosensitivity based on nanocrystalline TiO₂ films. *Thin Solid Films*. 2012;**520**:7144–7146
- [11] Lv K, Zhang M, Liu C, Liu G, Li H, Wen S, Chen Y, Ruan S. TiO₂ ultraviolet detector based on LaAlO₃ substrate with low dark current. *Journal of Alloys and Compounds*. 2013;**580**:614–617
- [12] Selman AM, Hassan Z, Husham M, Ahmed NM. A high-sensitivity, fast-response, rapid-recovery p–n heterojunction photodiode based on rutile TiO₂ nanorod array on p-Si(1 1 1). *Applied Surface Science*. 2014;**305**:445–452
- [13] Liu G, Tao C, Zhang M, Gu X, Meng F, Zhang X, Chen Y, Ruan S. Effects of surface self-assembled NH₄⁺ on the performance of TiO₂-based ultraviolet photodetectors. *Journal of Alloys and Compounds*. 2014;**601**:107

- [14] Yang J, Jiang Y-L, Li L-J, Muhire E, Gao M-Z. High-performance photodetectors and enhanced photocatalysts of two-dimensional TiO₂ nanosheets under UV light excitation. *Nanoscale*. 2016;**8**:8170–8177
- [15] Zu X, Wang H, Yi G, Zhang Z, Jiang X, Gong J, Luo H. Self-powered UV photodetector based on heterostructured TiO₂ nanowire arrays and polyaniline nanoflower arrays. *Synthetic Metals*. February 2015;**200**:58–65
- [16] Liu B, Aydil ES. Growth of oriented single-crystalline rutile TiO₂ nanorods on transparent conducting substrates for dye-sensitized solar cells. *Journal of the American Chemical Society*. 25 March 2009;**131**:3985–3990
- [17] Cao C, Hu C, Wang X, Wang S, Tian Y, Zhang H. UV sensor based on TiO₂ nanorod arrays on FTO thin film. *Sensors and Actuators B: Chemical*. 2011;**156**:114–119
- [18] Meng L, Chen H, Li C, dos Santos MP. Preparation and characterization of dye-sensitized TiO₂ nanorod solar cells. *Thin Solid Films*. 2015;**577**:103–108
- [19] Binetti E, El Koura Z, Bazzanella N, Carotenuto G, Miotello A. Synthesis of mesoporous ITO/TiO₂ electrodes for optoelectronics. *Materials Letters*. 2015;**139**:355–358
- [20] Chen JB, Wang CW, Kang YM, Li DS, Zhu WD, Zhou F. Investigation of temperature-dependent field emission from single crystal TiO₂ nanorods. *Applied Surface Science*. 2012;**258**:8279–8282
- [21] Xie Y, Wei L, Li Q, Chen Y, Liu H, Yan S, Jiao J, Liu G, Mei L. A high performance quasi-solid-state self-powered UV photodetector based on TiO₂ nanorod arrays. *Nanoscale*. 2014;**6**:9116–9121
- [22] Yanru X, Lin W, Qinghao L, Yanxue C, Shishen Y, Jun J, Guolei L, Liangmo M. High-performance self-powered UV photodetectors based on TiO₂ nano-branched arrays. *Nanotechnology*. 2014;**25**:075202
- [23] Zhang M, Li D, Zhou J, Chen W, Ruan S. Ultraviolet detector based on TiO₂ nanowire array-polymer hybrids with low dark current. *Journal of Alloys and Compounds*. 2015;**618**:233–235
- [24] Yan P, Wu Y, Liu G, Li A, Han H, Feng Z, Shi J, Gan Y, Li C. Enhancing photoresponsivity of self-powered UV photodetectors based on electrochemically reduced TiO₂ nanorods. *RSC Advances*. 2015;**5**:95939–95942
- [25] Yusoff MM, Mamat MH, Malek MF, Suriani AB, Mohamed A, Ahmad MK, Alrokayan SAH, Khan HA, Rusop M. Growth of titanium dioxide nanorod arrays through the aqueous chemical route under a novel and facile low-cost method. *Materials Letters*. 2016;**164**:294–298
- [26] Cozzoli PD, Kornowski A, Weller H. Low-temperature synthesis of soluble and processable organic-capped anatase TiO₂ nanorods. *Journal of the American Chemical Society*. 2003;**125**:14539–14548

- [27] Li Y, Liu J, Jia Z. Morphological control and photodegradation behavior of rutile TiO₂ prepared by a low-temperature process. *Materials Letters*. 2006;**60**:1753–1757
- [28] Iraj M, Nayeri FD, Asl-Soleimani E, Narimani K. Controlled growth of vertically aligned TiO₂ nanorod arrays using the improved hydrothermal method and their application to dye-sensitized solar cells. *Journal of Alloys and Compounds*. 2016;**659**:44–50
- [29] Feng X, Shankar K, Varghese OK, Paulose M, Latempa TJ, Grimes CA. Vertically aligned single crystal TiO₂ nanowire arrays grown directly on transparent conducting oxide coated glass: Synthesis details and applications. *Nano Letters*. 12 November 2008;**8**:3781–3786