Article

Oxygen-deficient bismuth tungstate and bismuth oxide composite photoanode with improved photostability

Hoi Ying Chung a, Weijian Chen b,c, Xiaoming Wen c, Judy N. Hart d, Hao Wu a, Yuekun Lai e, Rose Amal a, Yun Hau Ng a,b,*

a Particles and Catalysis Research Group, School of Chemical Engineering, The University of New South Wales (UNSW) Sydney, NSW 2052, Australia
b School of Photovoltaic and Renewable Energy Engineering, The University of New South Wales (UNSW) Sydney, NSW 2052, Australia
c Centre for Micro-Photonics, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Melbourne, VIC 3122, Australia
d School of Materials Science and Engineering, The University of New South Wales (UNSW) Sydney, NSW 2052, Australia
e National Engineering Laboratory for Modern Silk, College of Textile and Clothing Engineering, Soochow University, Suzhou 215123, China

A R T I C L E   I N F O

Article history:
Received 28 February 2018
Received in revised form 15 May 2018
Accepted 1 June 2018
Available online 27 June 2018

Keywords:
Bismuth oxide
Bismuth tungstate
Photocorrosion

A B S T R A C T

A homogeneous layer of Bi2O3-Bi14WO24 composite (BWO/Bi2O3) thin film was fabricated using a combination of electrodeposition and thermal treatment. The evenly distributed Bi14WO24 component within the Bi2O3 layer was found to be important in stabilising the photoelectrochemical performances of Bi2O3 photoanode by promoting the photoelectron transport. The unmodified Bi2O3 suffered from severe photocorrosion as proven by X-ray diffraction (XRD) and inductively coupled plasma (ICP) analyses while the Bi2O3 layer was found to be important in stabilising the photoelectrochemical performances of Bi2O3 photoanode by promoting the photoelectron transport. The unmodified Bi2O3 suffered from severe photocorrosion as proven by X-ray diffraction (XRD) and inductively coupled plasma (ICP) analyses while the composite thin film was active without noticeable activity decay for at least 3 h of illumination. This strategy might be applicable to other photocatalysts with stability issues.

© 2018 Science China Press. Published by Elsevier B.V. and Science China Press. All rights reserved.

1. Introduction

The development of photoactive semiconductors for photoelectrochemical (PEC) water splitting has gathered attention within the research community as it is potentially a green way to produce renewable hydrogen using sunlight and water [1]. In an ideal PEC water splitting system, the presence of both a photoanode and a photocathode is needed to drive the photolysis of water (i.e., water reduction on the photocathode). The water oxidation reaction requires transfer of four electrons to generate molecular O2, whereas only two electrons are needed for the water reduction process. Thus, it is generally perceived that the development of an efficient photoanode is challenging [2]. Although TiO2 has been the most widely studied photoanode for PEC water oxidation owing to its highly oxidising valence band, its intrinsic limitation in absorbing visible light has triggered further research into alternative semiconductors that can absorb both the ultraviolet and the visible light parts of the solar spectrum.

Bismuth oxide (Bi2O3) is a semiconductor with a direct transition band gap of ca. 2.8 eV, which suggests its photoexcitation can be prompted by visible light with wavelength shorter than 445 nm. Together with its high refractive index, dielectric permittivity, and high ion and photo-conductivity, Bi2O3 appears to be suitable for a range of photo-related applications. Furthermore, Bi2O3 can be conveniently synthesised using various methods including electrodeposition, hydrothermal synthesis, and solid-state reactions [3–5]. Photocatalytic activities of Bi2O3 in organic degradation, dye decolourisation, and water oxidation have been reported [6,7]. However, it was observed by Hajra and co-workers [8] that a Bi2O3 photoanode suffered from a significant loss of photocurrent. Rapid decay of photocurrent was observed in the first 100 s and almost all photoresponse disappeared after 15 min of UV–visible (UV–Vis) light illumination. Similarly, Shaikh et al. [9] also reported the benefits of introducing ZnO as a surface passivation layer on top of a Bi2O3 photoanode to improve its photoactivity in a dye-sensitised solar cell. Combined with our results, which will be discussed in the following sections, the issue of Bi2O3 photostability is apparent and it needs to be addressed.

In this work, oxygen-deficient bismuth tungstate (Bi14WO24) was homogeneously introduced into Bi2O3 to facilitate efficient charge transfer upon photoexcitation and to provide a protective layer that can minimise the accumulation of excited charges that lead to the photocorrosion of Bi2O3. Unlike the commonly used surface passivation techniques that usually yield two-distinct layers (e.g., ZnO on a Bi2O3 film [9], TiO2/CuO on a Cu2O film [10], Nb2O5 on a TiO2 film [11]), the unique characteristic of the
composite Bi$_4$WO$_{24}$ and Bi$_2$O$_3$ (hereafter referred to as BWO/Bi$_2$O$_3$ film) photoanode reported herein is the absence of a distinct interface between the two components. The nature of the homogenous mixture of Bi$_4$WO$_{24}$ and Bi$_2$O$_3$ is analogous to a solid solution. With this intimate contact, the excited charge shuttling between the two components is favourable. A photocurrent can be produced by the composite film for at least 3 h under continuous illumination without decay. In contrast, for the unmodified Bi$_2$O$_3$ photoanode, 80% of the photoresponse was lost in 1.5 h. Thus, the strategy demonstrated in this work of introducing a homogeneously distributed passivation component is useful and might be applicable to other unstable photovoltaic thin film materials.

2. Materials and methods

2.1. Preparation of BWO/Bi$_2$O$_3$ film

All reagents were purchased from Sigma-Aldrich and used as received without further purification. Transparent conducting fluorine-doped tin oxide (FTO) substrates (1.5 cm × 5 cm in size) were cleaned sequentially in acetone, ethanol and water, under sonication and dried in air before use. Pure Bi metal was deposited on the cleaned FTO using the pulse electrodeposition method developed by another group [12]. A standard three-electrode cell configuration was used for electrodeposition, with FTO as the working electrode, Pt foil as the counter electrode, and Ag/AgCl (1 mol/L KCl) as the reference electrode. An ethylene glycol solution containing 20 mmol/L of Bi(NO$_3$)$_3$·5H$_2$O was used as the plating electrolyte. Typically, a FTO substrate of dimensions 1.5 cm × 2 cm was immersed in the electrolyte, and a continuous waveform of a cathodic pulse (−1.2 V, 0.5 s) and relaxation voltage pulse (0 V, 2 s) were then being applied alternately for 7,200 cycles to result in the deposition of Bi particles on the substrate. This waveform was generated by an AUTOLAB potentiostat combined with Nova software. The employment of the 2 s relaxation time was to allow Bi$^{3+}$ ions to be replenished at the surface, which can increase the nucleation density of Bi on the working electrode to achieve a better deposit coverage. After this pulse electrodeposition process, the Bi-deposited thin films were carefully rinsed with ethanol and dried by blowing air. A 200 μL ethylene glycol was subsequently dropped on one of the Bi-deposited thin films, following by calcination in air at 600 °C for 4 h to provide a superior attachment on the FTO. The Bi$_2$O$_3$ film was obtained after calcination. To form a composite of BWO/Bi$_2$O$_3$, 200 μL of Na$_2$WO$_4$·2H$_2$O (0.75 mol/L) was dropped on the Bi metal layer prior to calcination in air at 600 °C for 4 h.

2.2. Characterisation of BWO/Bi$_2$O$_3$ films

The phase purity and crystallinity of the product were analysed by PANalytical Empyrean thin-film X-ray diffraction (XRD) using Cu Kα radiation (λ = 1.5406 Å) with a voltage of 45 kV and current of 40 mA at room temperature. Rietveld refinement is done by fitting and analysing the XRD pattern diffractogram using the High Score program developed by PANalytical. Scanning electron microscopy (SEM) images were obtained with a FEI Nova NanoSEM 450 FESEM microscope operated at 5 kV to examine the morphology of the thin film. The elemental mapping and distribution were determined by X-ray energy dispersion spectrum (EDS). Transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) images were obtained by Philips CM200 instrument in bright field mode. The UV–Vis absorption spectra were recorded using Shimadzu UV-3600 spectrophotometer, with BaSO$_4$ powder used as the reference. The absorbance was calculated from the measured reflectance using Kubelka-Munk function to identify the band gaps of the films. The elemental composition was quantified by PerkinElmer quadrupole Nexion inductively coupled plasma mass spectrometry (ICP-MS). X-ray photoelectron spectroscopy (XPS) was carried out using ESCALAB250Xi (Thermo Scientific) with a mono-chromated Al Kα source. All the peak positions was calibrated using the binding energy of C 1 s at 284.8 eV. The time-resolved fluorescence (PL decay) was conducted by the time-correlated-single-photon-counting (TCSPC) on Microtime-200 system (Picoquant) with excitation of a 405 nm pulsed laser. Using the bi-exponential decay function $y = A_1\exp(-t/t_1) + A_2\exp(-t/t_2)$, each PL decay trace can be nicely fitted to determine the decay times. The average lifetimes are obtained using $\tau_{av} = (A_1t_1^2 + A_2t_2^2)/(A_1t_1^2 + A_2t_2^2)$ [13].

2.3. Photoelectrochemical test

All photoelectrochemical measurements including electrochemical impedance spectroscopy (EIS) were conducted in an electrolyte of 0.1 mol/L Na$_2$SO$_4$ (pH 6.8–7.2) with a three-electrode system (Pt foil and Ag/AgCl were used as the counter electrode and reference electrode, respectively) using a potentiostat (Autolab model PGSTAT 12) with frequency response analyser (Autolab FRA2 modules). The light source was a 300 W Xe lamp. Back illumination was performed with an exposed thin film area of 0.72 cm$^2$. The flat band potential of the thin films was estimated by Mott-Schottky analysis, where the measurement was performed at frequency of 500 Hz.

3. Results and discussion

Upon pulse electrodeposition, a compact black layer of metallic Bi was evenly coated on the FTO substrate (Fig. 1a). Pulse electrodeposition has the obvious merit of depositing a dense layer. Achieving a dense layer of Bi is important because it serves as the seeding precursor for the subsequent conversion to Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$ thin films. SEM images (Fig. S1 online) of the Bi-deposited FTO substrates prepared using pulse and non-pulse systems clearly differentiate the quality of the Bi-deposited films. As can be seen in Fig. S1 (online), the coverage of metallic Bi on FTO was comprehensive for the pulse electrodeposited film, while the continuous non-pulse electrodeposition produced a patchy distribution of metallic Bi with a significant portion of the FTO surface found to be exposed and uncovered. The difference in coverage is due to the relaxation pulse (0 V, 2 s) that allows the replenishment of Bi$^{3+}$ ions at the FTO surface for subsequent deposition [12]. All the Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$ films examined in this work were, therefore, prepared using the pulse electrodeposited Bi.

After the thermal treatment of the Bi-deposited films with or without W precursor addition, the films had a yellowish appearance (Fig. 1a) suggesting successful formation of Bi$_2$O$_3$ and BWO/ Bi$_2$O$_3$ (these two materials usually have a yellow colour due to their narrow optical band gaps of around 2.8 eV). Compact but featureless films were seen from the SEM images of the resultant Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$ films (Fig. 1b). Fig. 1c shows the XRD patterns of the prepared thin films. Although both films are highly crystalline, the bare Bi$_2$O$_3$ film obtained from direct annealing was confirmed to be the monoclinic phase and indexed with the JCPDS No. 03-2034 pattern. The additional W precursor treatment yielded a mixture of monoclinic Bi$_4$WO$_{24}$ (JCPDS No. 80-5931) and Bi$_2$O$_3$ after calcined. The relative amounts of Bi$_4$WO$_{24}$ and Bi$_2$O$_3$ in the BWO/Bi$_2$O$_3$ film were determined using Rietveld refinement. The film was estimated to be composed 29.1% Bi$_2$O$_3$ with the rest Bi$_4$WO$_{24}$ (Fig. S2 online). Bi$_4$WO$_{24}$ is considered as an oxygen-deficient or bismuth-rich bismuth tungstate [14]. Note that the Bi$_2$O$_3$ would not be fully transformed into
Bi$_{14}$WO$_{24}$ with the addition of much higher concentration of tungsten precursors. The XPS result illustrates Bi$_{14}$WO$_{24}$ was made composite with Bi$_2$O$_3$ (Fig. S3 online). In the Bi 4f spectrum, the Bi 4f peaks of Bi$_2$O$_3$ thin films are located at 158.5 and 163.8 eV, which are attributed to Bi$^{3+}$ [15]. However, the doublet Bi 4f peak is shifted to a lower binding energy for ca. 0.2 eV, proposing a change in the interfacial structure due to the introduction of W [16]. In the W 4f spectrum, strong signals are detected in the composite of BWO/Bi$_2$O$_3$ thin film only. The binding energy of the doublet peak is located at 34.5 and 36.6 eV, and they are assigned to the W 4f$_{7/2}$ and W 4f$_{5/2}$ of the W$^{6+}$ species, respectively [17,18].

As the formation of the BWO/Bi$_2$O$_3$ composite is driven by the surface-to-bulk diffusion of WO$_4^{2-}$ ions into the film during the simultaneous formation of Bi$_2$O$_3$ at elevated temperature, the homogeneity of the tungstate distribution throughout the bulk BWO/Bi$_2$O$_3$ needs to be examined. Our previous works on hydrothermally transforming WO$_3$ into Bi$_2$WO$_6$ and MoO$_3$ into Bi$_2$MoO$_6$ had found a gradient in bismuth concentration through the film thickness [19,20]. It is, therefore, also interesting to characterise this BWO/Bi$_2$O$_3$ film to obtain insight into these two different synthesis methods. Fig. 2 shows the cross-sectional SEM-EDS images of the BWO/Bi$_2$O$_3$ film with its relevant elemental mapping. The distribution of tungsten is homogeneous through the film, indicating the uniform dispersion of Bi$_{14}$WO$_{24}$ within the composite film. There is no obvious region within the film showing separation of Bi$_{14}$WO$_{24}$ from Bi$_2$O$_3$. Comparing with the cross section SEM-EDS images of bulk Bi$_2$O$_3$, no W element was detected along the film (Fig. S4 online). This “solid-solution”–like composite of Bi$_{14}$WO$_{24}$ and Bi$_2$O$_3$ is expected to be favourable for photoexcited charge transfer owing to the intimate contact between the components.

Further evidence of this well-mixed BWO/Bi$_2$O$_3$ composite is obtained using HRTEM analysis. Fig. 3 shows TEM images of the bare Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$. Their respective high resolution images demonstrate the polycrystalline nature of the materials. Lattice fringes with spacing of 2.75 and 3.22 Å were measured for the BWO/Bi$_2$O$_3$ composite, corresponding to the (103), (301), (231) and (150) planes of monoclinic Bi$_{14}$WO$_{24}$. The lattice spacing of 2.70, 3.25 and 3.31 Å observed for both the Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$ films are consistent with the (1 21), (1 20), (1 11) and (1 12) planes of monoclinic Bi$_2$O$_3$. Hence, the combination of XRD, XPS, SEM-EDX, and HRTEM results confirm the successful formation of Bi$_{14}$WO$_{24}$ throughout the Bi$_2$O$_3$ films. More interestingly, the Bi$_{14}$WO$_{24}$ was homogeneously distributed throughout the film, which is expected to be advantageous for the transport of photocharges upon excitation.

The optical band gaps of the Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$ films were determined using UV–Vis absorption spectroscopy. The UV–Vis absorption spectra in Fig. 4 show the absorption edges of Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$ at a similar wavelength, λ ≈ 430 nm. The optical band gap ($E_g$) derived from the Tauc plot (inset of Fig. 4) is 2.9 eV, consistent with previous reports of Bi$_2$O$_3$ [21]. Although both the bare Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$ films have the similar light absorption, other electronic characterisation suggests that Bi$_2$O$_3$ has superior properties for electron transportation. Fig. 5a and b shows the Mott-Schottky and EIS conductance plots of both films. In the Mott-Schottky analysis, capacitance of the space charge layer (C) of the film was measured as a function of applied potential. The conductivity type and charge carrier density (or donor density) of the films can be determined from the results [22,23]. The latter can be calculated by the following Eq. (1):

![Fig. 2.](image) Cross-sectional SEM image of the BWO/Bi$_2$O$_3$ film and its elemental (Bi, W and O) distribution through the film.
\[ N_d = \left( \frac{2}{e_0 \varepsilon_0 e_0} \right) \left( \frac{d}{dV} \right)^{-1} \]  

where \( e_0 \) is the electron charge, \( \varepsilon \) is the dielectric constant, \( \varepsilon_0 \) is the permittivity of vacuum, \( N_d \) is the donor density, \( V \) is the applied bias at the electrode, and \( C \) is the capacitance of the space charge layer. According to Eq. (1), the donor densities in the different films can be qualitatively compared since it is inversely proportional to the gradient of the Mott-Schottky plot.

Both the bare Bi\(_2\)O\(_3\) and BWO/Bi\(_2\)O\(_3\) films demonstrate a positive slope in the Mott-Schottky plots, indicating that they are n-type semiconductor [22]. The bare Bi\(_2\)O\(_3\) film gives a lower gradient than the BWO/Bi\(_2\)O\(_3\) film, suggesting that it has a higher charge density. Higher donor density could enhance the PEC performance as the charge transfer between the oxide layer and FTO substrate is improved. The flat band potential (\( F_b \)) of Bi\(_2\)O\(_3\) is at +0.37 V versus normal hydrogen electrode (NHE) at pH 0, which is comparable with the literature [23]. Given that to \( F_b \) of BWO/Bi\(_2\)O\(_3\) has shifted to +0.11 V vs. NHE at pH 0, it suggests that the band structure of this composite has been altered. Fig. 5b shows the EIS conductance as a function of frequency for the Bi\(_2\)O\(_3\) and BWO/Bi\(_2\)O\(_3\) films, the curve is correlated to the electrical behaviour at the interface of the photoelectrode within the system. In the high frequency response (>100 Hz) the conductivity is dominated by the interface between the film and the Na\(_2\)SO\(_4\) electrolyte. The conductance of both films at the high frequency region is identical for both films. The other frequency regions, the conductance of the bulk oxide films (medium frequency range, 1–100 Hz) as well as the conductance at the interface of the oxide and FTO substrate (low frequency range, 10 mHz–1 Hz) can be evaluated. The medium frequency region is ascribed to the electrical ability of the interior of the bulk oxide film, while the low frequency region shows the conductance at the interface of the oxide and FTO substrate. The conductance of the bulk Bi\(_2\)O\(_3\) is only marginally higher than that

Fig. 3. (Color online) TEM images of (a) Bi\(_2\)O\(_3\) and (c) BWO/Bi\(_2\)O\(_3\) films and (b, d) their corresponding high resolution images showing the lattice spacing.

Fig. 4. (Color online) UV-Vis absorption spectra of Bi\(_2\)O\(_3\) and BWO/Bi\(_2\)O\(_3\).
of BWO/Bi₂O₃, indicating the lower charge diffusion of the composite material. However, the bare Bi₂O₃ has significantly better electron mobility at the interface with the FTO substrate.

The photocurrent densities measured under constant voltage (amperometry, Fig. 6a) confirm that both the Bi₂O₃ and BWO/Bi₂O₃ films are photoresponsive, and the anodic photocurrent verifies their n-type semiconducting behaviour [24]. The bare Bi₂O₃ film demonstrated higher anodic photocurrent than that of the BWO/Bi₂O₃ film. This was also supported by the linear sweep voltammogram measurement where higher photocurrent was displayed by the bare Bi₂O₃ film across the entire potential bias compared to the composite film (Fig. S5 online). This is consistent with the better electrochemical properties (donor density and conductivity) indicated by Mott-Schottky and EIS conductance analyses.

Although the photocurrent generation was higher for the bare Bi₂O₃ film (as expected), the photocurrent decayed noticeably and rapidly within 10 min of on-off illumination cycling, while the photoresponse of BWO/Bi₂O₃ remained unchanged. This observation of photo-instability for Bi₂O₃ is consistent with the previous work by Hajra et al. [8]. To further investigate the stability of both films under illumination, the photocurrent decay of the Bi₂O₃ and BWO/Bi₂O₃ films was measured over an extended 3-h period of continuous illumination (Fig. 6b). The photocurrent decay in Fig. 6b is presented as the ratio of the measured photocurrent (I) to the initial photocurrent (Iₒ). The photocurrent density half-life for the Bi₂O₃ film was ca. 50 min, i.e. half of the photoactivity was lost in less than 1 h, indicating that the bare Bi₂O₃ film is not ideal for a photoelectrochemical system due to its photo stability issue. After 2 h of illumination, the Bi₂O₃ film lost almost all of its photoresponse. In contrast, the BWO/Bi₂O₃ film was able to maintain its photocurrent density over the whole illumination duration without noticeable decay. Thus, the advantage of introducing Bi₁₄WO₂₄ to form a composite with Bi₂O₃ can be seen in the photostability improvement, albeit its relatively low absolute photocurrent value can be further enhanced by other modifications [25].

The photocurrent decay of the Bi₂O₃ film was accompanied by the formation of a new crystal phase after the 3-h illumination period, as observed in XRD diffractogram (Fig. 7a). An additional high-intensity peak was observed at 27.9° for the Bi₂O₃ film after illumination, which can be indexed to either Bi₁₄SO₂₄ or Na₂O. The formation of these new compounds is reasonable as Na₂SO₄ was used as the electrolyte in the photoelectrochemical measurement. In contrast, the XRD patterns of the BWO/Bi₂O₃ film before and after the illumination are essentially the same (Fig. 7b).

Furthermore, the significant loss of photocurrent in the Bi₂O₃ film can also be associated with anodic photocorrosion (i.e., self photo-oxidation of Bi₂O₃). ICP-MS characterisation shows there was 175 µg/L of Bi ions leach into the electrolyte used for PEC measurement of the Bi₂O₃ after 3-h illumination. This type of photocorrosion can occur when the interfacial transfer of photoexcited holes is slow and subsequently leads to the accumulation of holes that induces self-oxidation. The introduction of Bi₁₄WO₂₄ to Bi₂O₃ facilitates the transfer of photoexcited charges. With the promotion of excited charge transfer, accumulation of holes within a single component is prevented and photocorrosion is suppressed. Fig. 7c shows the postulated band energy structure of bismuth oxide and tungstate based on previous reports [26–29].
Mott-Schottky plot has illustrated the Fermi level has been shifted upward for BWO/Bi$_2$O$_3$ composited. Owing to the band alignment, the excited electrons from the Bi$_{14}$WO$_{24}$ are transferred to bismuth oxide while the migration of holes happens in the opposite direction. This promoted charge transfer can be indicated by the prolonged charge lifetime evaluated by the time-resolved PL. Based on the PL results of the thin films (Fig. 8), decay time for the charges in the BWO/Bi$_2$O$_3$ composite ($\tau_{\text{average}} = 1.85$ ns) is slower than that of the Bi$_2$O$_3$ ($\tau_{\text{average}} = 0.94$ ns). Supported by the close proximity of the components as evidenced by the PL decay, SEM-EDS and HRTEM, this improved charge transfer is expected to contribute to the long-term stability of BWO/Bi$_2$O$_3$.

4. Conclusions

Although Bi$_2$O$_3$ is a potential photoactive semiconductor with some ideal electronic properties, its instability under prolonged illumination is a significant issue. In this work, we have demonstrated a strategy to stabilise Bi$_2$O$_3$ by the introduction of a homogeneously distributed Bi$_{14}$WO$_{24}$ component. This composite film can be prepared by a method combining pulse electrodeposition and thermal treatment. Compared with bare Bi$_2$O$_3$, the composite film has much more stable photoactivity under long-term illumination. The photostability improvement is attributed to the improved charge transfer between the two semiconductors which in turn suppresses the photocorrosion. This strategy might be applicable to other photocatalysts with stability challenges.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the Australian Research Council under the Laureate Fellowship Scheme (FL140100081). The authors acknowledge the facilities, and the scientific and technical assistance of the Electron Microscope Unit, The University of New South Wales.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scib.2018.06.012.

References


Fig. 7. (Color online) XRD patterns measured before and after PEC measurement for (a) Bi$_2$O$_3$ and (b) BWO/Bi$_2$O$_3$. (c) Energy band structure for the BWO/Bi$_2$O$_3$ films.

Fig. 8. Time-resolved fluorescence of Bi$_2$O$_3$ and BWO/Bi$_2$O$_3$ thin film.


