Effect of pH on visible-light-driven photocatalytic degradation of facile synthesized bismuth vanadate nanoparticles

A Juliatt Josephine\textsuperscript{1,2}, C Ravi Dhas\textsuperscript{1} \textsuperscript{a}, R Venkatesh\textsuperscript{1}, D Arivukarasan\textsuperscript{1}, A Jennifer Christy\textsuperscript{1,2}, S Esther Santhoshi Monica\textsuperscript{1} and S Keerthana\textsuperscript{1}

\textsuperscript{1}PG and Research Department of Physics, Bishop Heber College (Autonomous), Tiruchirappalli—620 017, India
\textsuperscript{2}PG and Research Department of Physics, Holy Cross College (Autonomous), Tiruchirappalli—620 017, India

E-mail: ravidhasc@gmail.com and cravidhas@gmail.com

Keywords: co-precipitation, bismuth vanadate, rhodamine B, photocatalyst, dye degradation

Abstract

Bismuth vanadate (BiVO\textsubscript{4}) nanoparticles were synthesized by a simple co-precipitation method for different pH conditions (9, 10 and 11). The XRD patterns revealed that the synthesized nanoparticles belong to monoclinic single-phase BiVO\textsubscript{4} which was again confirmed from Raman studies. The chemical state of the elements in BiVO\textsubscript{4} and surface morphology were investigated using XPS and SEM analysis respectively. The optical absorption and PL studies revealed wide absorption in the visible region with strong emission at 520 nm. The efficiency of the samples was examined from the photocatalytic degradation of Rhodamine B dye.

1. Introduction

Photocatalytic water splitting and dye degradation under the visible-light solar spectrum is a promising approach to address environmental threats on a global scale. This, in turn, interested the researchers to develop facile visible-light-driven photocatalysts for the photodegradation of organic pollutants that are being continuously released from the food and textile industries [1–5]. In recent times, visible-light-responsive photocatalysts paved the way for the utilization of visible-light in the solar spectrum. The applications of nanoparticles are highly significant and utilized in various fields such as catalysis, semiconductors, pharmaceutical products and electronics [6]. Among all inorganic materials that are produced at the nanometer scale, metal oxides are the most attractive candidates from a technological and scientific point of view [7].

Among the complex metal oxides, one of the desirable photo-anode materials which exhibit visible-light photoactivity is bismuth vanadate (BiVO\textsubscript{4}) [8, 9]. BiVO\textsubscript{4} is categorized under the ternary bismuth oxide compound group, Bi–M–O (W, V, Mo, Ta and Nb), due to its distinctive physical and chemical properties. BiVO\textsubscript{4} has been probed-out to be an acousto-optical, ferroelastic, ion conductive and pigmentary material [10]. It is noted that the synthetic BiVO\textsubscript{4} has three crystalline phases such as monoclinic scheelite, tetragonal zircon and tetragonal scheelite structure. On examining the bandgap of monoclinic scheelite structure with its relatively narrow bandgap of 2.4 eV possesses high photocatalytic performance under visible-light illumination than tetragonal zircon and tetragonal scheelite phases (2.9–3.1 eV) [11–13]. Due to this peculiar nature of monoclinic bismuth vanadate (m-BiVO\textsubscript{4}), it has a profound attraction for the researchers for the degradation of organic pollutants.

The different methods to synthesize m-BiVO\textsubscript{4} are the aqueous method, homogeneous precipitation, co-precipitation, solution combustion method, sonochemical method, hydrothermal and ionothermal treatment, reverse-micro emulsion technique [14–21], etc, where its visible-light photocatalytic activity has been demonstrated. The photocatalytic activity was affected mainly by four factors including the absorbance, photonic efficiency, surface area and photo-carrier transport properties [22]. Most of the research work on synthesizing BiVO\textsubscript{4} nanoparticles is carried out using the hydrothermal method which is laborious, time-consuming and needs sophisticated and highly expensive Teflon lined autoclave [23–25]. In this present work, we have synthesized BiVO\textsubscript{4} nanoparticles using a co-precipitation method where the total duration for
corresponding pH levels to 9, 10 and 11 respectively. The obtained yellow precipitate was separated, at 450 °C for 3 h to form BiVO4 nanoparticles. To the best of our knowledge, there are seldom reports synthesizing was about only 8 h. It is to identify a proper pH condition to tailor the crystalline electronic and morphological properties of BiVO4 nanoparticles. To the best of our knowledge, there are seldom reports describing the role of pH on the photocatalytic activity of BiVO4 nanoparticles by the additive-free co-precipitation method. The factor pH is one of the crucial parameters that play a pivotal role in the synthesis of nanoparticles due to the surface charge properties of the photocatalyst. From recent reports [26–28], it was observed that the synthesis of BiVO4 in acidic medium results in the formation of mixed phases (tetragonal and monoclinic). The pH from acidic to basic favors crystallization of BiVO4 in monoclinic structure and hence in this work it was aimed to study the structural, optical and photocatalytic behavior of BiVO4 synthesized in basic medium.

Our research team has previously reported a paper on BiVO4 nanoparticles synthesized for different post-calcination treatment (450, 550 and 650 °C) by co-precipitation method [29] and in this present work, the effect of synthesizing pH conditions over the photocatalytic properties of BiVO4 nanoparticles was prepared by low-cost and time-consuming co-precipitation method. The structural, morphological, chemical state analysis and optical properties of the synthesized BiVO4 nanoparticles were investigated using x-ray diffraction (XRD), scanning electron microscopy (SEM) and UV–vis, Raman spectroscopy, x-ray photoelectron spectroscopy (XPS), photoluminescence and photocatalytic studies.

2. Materials and methods

2.1. Chemicals

In this synthesis process Bismuth nitrate pentahydrate Bi(NO3)3·5H2O (Loba Chemie, India), Ammonium metavanadate (NH4VO3) (SD Fine, India), nitric acid (HNO3) (Merck), sodium hydroxide (Merck), Rhodamine B (Loba Chemie, India) were used. The deionized water was used for the experimental process.

2.2. Synthesis

The BiVO4 nanoparticles were prepared as follows: initially, 0.1 M of Bi(NO3)3·5H2O and 0.2 M of NH4VO3 were added separately in 40 ml of dilute HNO3 solution and stirred continuously for 30 min. The Bi(NO3)3 solution was added drop by drop into the NH4VO3 solution. The mixed solution by applying the temperature of about 50 °C was stirred vigorously until the solid dissolved completely. NaOH solution was used to adjust the corresponding pH levels to 9, 10 and 11 respectively. The obtained yellow precipitate was separated, filtered, washed with distilled water and ethanol and dried in the open hot plate. Finally, the dried powders were calcined at 450 °C for 3 h to form BiVO4 nanoparticles.

2.3. Characterization

The crystal structures of BiVO4 samples were examined by powder x-ray diffraction (X’Pert PRO PANanalytical). Raman spectra were recorded with Micro Raman spectrometer (Reinshaw invia make). The morphological changes of the samples were observed using the scanning electron microscopy (SEM) (VEGA3 TESCAN) with energy dispersive analysis (EDS) (Bruker). The UV–vis diffuse reflectance spectrum of the samples was recorded on a UV—vis—NIR Spectrophotometer—SHIMADZU make. The photoluminescence spectra were recorded with Varian Cary Eclipse fluorescence Spectrometer.

2.4. Photocatalytic experiment

The photocatalytic experiment was carried out in Heber Visible Annular Type Photo reactor. The prepared BiVO4 photocatalyst was plunged in Rhodamine B (RhB) dye solution (10 mg l−1) and stirred for 1 h in the dark to make certain adsorption–desorption equilibrium between the photocatalyst and dye solution. A tungsten halogen lamp (λ > 400 nm) was used as the light source which is placed within the double-walled quartz tube inside the reactor. The visible light irradiation was carried out in the photoreactor for 3 h. During the reaction, for every 30 min, a portion of the suspension was taken out to study the photodegradation using UV–vis spectrophotometer (Shimadzu UV–vis spectrometer).

3. Results and discussion

3.1. Crystal structure

The x-ray diffraction (XRD) pattern of synthesized BiVO4 nanoparticles for different pH at 9, 10 and 11 were shown in figure 1. The peaks present at 18.5°, 28.9°, 30.5° and 34.5° represent the crystallite planes of (011), (121), (040) and (200) respectively which holds good with clinobisvanite structure of m-BiVO4 (ICPDS 14–0688). It was a fact that when the pH of the solution changes from acidity to basicity, the predominant peak (121) of m-BiVO4 becomes stronger [30]. No other peaks related to secondary phases were observed in the XRD
patterns, suggesting that all the prepared samples have the same pure monoclinic structure. The average crystallite size was calculated using the Scherrer formula:

\[ D = \frac{K\lambda}{\beta \cos \theta} \text{ (nm)} \]  

where \(D\) is the mean crystallite size (nm), \(K\) - shape factor, \(\lambda\) - the wavelength of the x-ray radiation, \(\beta\) - the full width at half maximum (FWHM) of the diffraction peak and \(\theta\) - the angle of diffraction.

The microstrain \(\varepsilon\) and the dislocation density \(\delta\) were determined using the relations:

\[ \varepsilon = \frac{\beta \cos \theta}{4} \]  

\[ \delta = \frac{1}{D^2} \text{ (lines/m}^2\text{)} \]

The computed parameters were displayed in table 1. It was observed that the dislocation density and strain decrease when the pH value increases from 9 to 10. The decrease in dislocation density and microstrain values implies the improvement in the crystalline quality of nanoparticles [33]. Zheng et al [34] observed that the diffracted peaks were found to be narrower and stronger when the pH value increases from 9 to 10 and it becomes slightly weaker and broader when the pH value was increased further from 10 to 11, indicating that the

---

**Table 1.** Crystallographic parameters of BiVO₄ nanoparticles at different pH levels.

| Sample code | Crystallite size \(D\) (nm) | Lattice parameters (Å) | Dislocation density \(\delta \times 10^{15}\) (lines/m²) | Microstrain \(\varepsilon \times 10^{-3}\) |
|-------------|-----------------------------|------------------------|-------------------------------------------------|-------------------------------|
| pH 9        | 41                          | a=5.1709  b=5.0703  c=11.7321 | 0.594                                         | 0.8                           |
| pH 10       | 46                          | a=5.1737  b=5.0919  c=11.6921 | 0.472                                         | 0.7                           |
| pH 11       | 32                          | a=5.1796  b=5.0814  c=11.7618 | 0.976                                         | 1.1                           |

---

Figure 1. XRD of BiVO₄ nanoparticles for different pH 9, 10, 11.
crystallite size decreases beyond pH 11. The excess OH\(^{-}\) ions at higher pH hinder the growth of crystallites. There was almost no significant variation in the crystallite size of the synthesized BiVO\(_4\) nanoparticles. From the XRD study, it was observed that more background radiation resulted from the samples synthesized at pH 9 and 11 which was an indication of higher native crystalline defects. These defects might be the cause for the poor photocatalytic activity which will act as traps/recombination centers for the excited charge carriers. The good crystallinity of the m-BiVO\(_4\) nanoparticles at pH 10 enhances the light-harvesting properties by increasing the mobility of charge carriers which minimize the defects\[^{24}\] leading to higher photocatalytic activity.

3.2. Raman spectra
Raman spectra of BiVO\(_4\) nanoparticles for different pH were shown in the figure 2. BiVO\(_4\) exhibits the symmetric and asymmetric deformation modes of VO\(_4^{3-}\) and the predominant peak at 820 cm\(^{-1}\) indicates the symmetric stretching mode of the V–O bond. From the Raman peaks, the formation of single-phase BiVO\(_4\) was in accordance with the XRD patterns. The broad peak at 355 cm\(^{-1}\) approves the symmetric deformation modes of the VO\(_4^{3-}\) tetrahedron\[^{29}\].

The bond length of the vanadium (V) and oxygen (O) in BiVO\(_4\) was calculated using the relation\[^{29}\];

\[
u (\text{cm}^{-1}) = 21349 \exp (-1.9176 R)
\]

where \(R\) represents the peak of VO\(_4\) stretching mode.

The bond length of ‘V’ and ‘O’ is calculated for E\(_g\) mode and the values were found to be 1.69 to 1.70 Å which was consistent with the previous report\[^{35}\]. No other impurity phases related to Bi and V and mixed oxides were observed. At pH 11, the FWHM increases due to Raman band and Raman widths which were responsible for the short-range order and crystalline nature, defects, disorders, aggregation of particles respectively\[^{36}\]. This was confirmed in XRD and SEM analysis, hence the Raman spectra confess that the sample at higher pH has lesser crystallinity and defects which reduce the photodegradation compared to the samples at lower pH.

3.3. Morphology
Figure 3 represent the SEM images of BiVO\(_4\) prepared by homogeneous co-precipitation method for different pH values which highly influence the crystal phase, shape and size. This significant change in the morphological shape, structures and growth processes of BiVO\(_4\) nanostructures was also noted in the previous research work\[^{33}\].

While increasing the pH, notable variations were observed in the morphologies of the BiVO\(_4\). When pH values were increased from 9 to 10, the surfaces of BiVO\(_4\) nanoparticles become smoother and on a further increase of pH from 10 to 11, the catalysts surface altered into a coarse and clustered form which tends to
agglomerate further. But the surface of BiVO₄ at pH 10 was more uniformly dispersed compared to other samples. At lower pH, the H⁺ ions were considerably higher than OH⁻ ions due to which the hydrolysis of Bi³⁺ ions confines the growth which plays a key role in the morphological variations. On the other hand, the concentration of Bi³⁺ ions was lessened due to the hydrolysis of the Bi³⁺ ions on increasing the pH [37]. Thus, in this reaction, there was a high concentration of free Bi³⁺ ions which tends to form large particle sizes of BiVO₄ because of the rapid crystal growth [11]. The amount of OH⁻ concentration was not sufficient for the crystallization process of BiVO₄ at low pH 9 which affects nucleation and growth. At pH 11, some of the free Bi³⁺ ions present in the reaction resulted in the heavy agglomeration and rough surface. At pH 10, hydrolysis of Bi(NO₃)₃ leads to a low concentration of Bi³⁺ ions, so large m-BiVO₄ nanocrystals were formed. The theory behind the m-BiVO₄ nanoparticle growth mechanism for different pH values was not found and the research findings were still in progress.

3.4. X-ray photoelectron spectroscopy
Figure 4(a) shows the wide energy range (0–1200 eV) XPS spectrum of BiVO₄ nanoparticle at pH 10. The binding energy levels (Bi 4f, V 2p, O 1s) along with Auger peaks (O KLL and V KLL) that were obtained from the wide scan spectra indicate the elements present in the material. The high-resolution and wide scan spectrum corresponding to Bi4f, V2p, O1s were corrected and plotted by referring to the binding energy of the C1s peak at 284.6 eV. No impurities or secondary phases other than Bi, V and O were confirmed. The obtained binding energy values were in good accordance with the previous reports [38]. Figures 4(b)–(d) shows the core level spectra of Bi, V and O elements. The two intense peaks observed at 158 and 163.3 eV correspond to Bi4f⁷/₂ and Bi4f⁵/₂ respectively. The peak splitting energy difference (5.3 eV) confirms the presence of Bismuth ions in the trivalent oxidation state. The core level spectra of Vanadium were inconsistent with 516.4 (V2p₃/₂) and 523.3 eV (V2p₁/₂), which was ascribed to the presence of V⁵⁺ species in BiVO₄. For Oxygen, the XPS spectra of O1s has an asymmetric peak centered at 529.5 eV incorporated with lattice oxygen O⁻² species (Oₐₐ₅).
3.5. Energy dispersive analysis

Figure 5 shows the energy dispersive x-ray analysis of BiVO$_4$ nanoparticles. The elemental composition of Bismuth (Bi), Vanadium (V) and Oxygen (O) presence was confirmed and the values were given in the inset table. The absence of other peaks reveals the purity of the material.

3.6. Photoluminescence

Room temperature photoluminescence emission spectra were recorded for the BiVO$_4$ nanoparticles at the wavelength of $\lambda_{exc}$ 315 nm. From figure 6, the low-intensity emission peak at 520 nm ($E_g = 2.33$ eV) refers to the near band edge emission (NBE) where recombination of the hole occurs from O2p orbitals of the valance band to the V3d orbital of the conduction band of VO$_4^{3-}$ [33]. The obtained NBE emission peak was coherent with the optical band gap values (2.2–2.4 eV) estimated from the Tauc plot [33, 39]. Because of the crystalline defects [40], the broad emission peak at 494 nm ($E_g = 2.51$ eV) may be due to the presence of oxygen vacancies which act as recombination centers. The smaller crystallite size hires high PL intensity and this phenomenon was reported by Quintana - Melgoza et al [41] stated that electronic properties such as chemical or ions, atomic arrangement and physical dimension will enhance the optical response of the material. The low intensity of the PL curve at pH 10 was due to the lesser recombination process that was mainly due to the presence of oxygen atoms which act as an electron capturer [42] and also due to the separation of charges from the photogenerated electron-hole pairs. Hence this material has a good characteristic approach towards photocatalytic applications. On the other hand, the high luminescence intensity for pH 11 implies that the photocatalytic performance was hindered by the presence of defects through charge recombination.

3.7. Optical properties

The optical properties of a semiconductor have an important role in the enhancement of electronic structure and photocatalytic activity. The optical absorbance was calculated from diffused reflectance spectra (Kulbelka-Munk units) [29]:

$$F(R)^{1/2} = [(1 - R^2) / 2R]^{1/2}$$  \hspace{1cm} (5)

In general, BiVO$_4$ was composed of hybridized Bi 6s and O 2p orbitals in the valence band and V 3d orbitals in the conduction band whereas the migration of photo-excited holes occurs due to the hybridized Bi 6s and O
2p orbitals in the valence band [43]. From figure 7(a) it was noticed that the optical absorption was increased with an increase in crystalline quality and rod-like morphology for pH 10 which cause the internal reflections that promote more photo-generated charge carriers.

The bandgap of the crystalline semiconductor was estimated from the equation [29]:

$$\alpha = A(\nu - E_g)^n$$

where, $E_g$ is energy bandgap, $h$ - Planck’s constant, $\nu$ - incident photon frequency, $\alpha$ - absorption coefficient and the ‘n’ value was 1 indicating the direct bandgap transition. From figure 7(b), the intercepts of the linear portion of the graph in the energy axis give the direct bandgap. The estimated direct bandgap values were found to be 2.3, 2.29 and 2.38 eV, for pH 9, 10 and 11 respectively. The bandgap energy (2.29 eV) ensures that BiVO$_4$ at
pH 10 has a monoclinic crystalline phase [33] which clearly demonstrates a good visible-light-driven photocatalyst synthesized by co-precipitation method.

3.8. Photocatalytic performance

The photocatalytic activity of BiVO₄ nanoparticles for different pH was observed by dye degradation in an aqueous solution of rhodamine B (RhB) at the absorption peak of 554 nm under visible-light illumination. The BiVO₄ catalysts were immersed in the RhB dye solution to attain adsorption and desorption equilibrium for a time period of 30 min. Blank tests were carried out to make certain that photocatalytic activity takes place between the catalyst and light. Figures 8(a)–(d) shows the time-dependent absorption spectral change and percentage of degradation for RhB dye under visible-light illumination. It was found that the absorption spectra peak ($\lambda = 554$ nm) decreases with an increase in reaction time. From the temporal changes observed the intensity of the absorption spectra of RhB decreases with respect to time which leads to the linear destruction of the chromophore rings.

The degradation rate was calculated using the relation [44];

$$\text{Degradation rate} = \frac{C - C_t}{C_0} \times 100\%$$  \hspace{1cm} (7)

where ‘$C_0$’—is initial concentration and ‘$C$’ - final concentration of dye solution measured at the time ‘$t$’ respectively. From the results, it was observed that BiVO₄ with pH 10 at 450 °C possesses 90 % of degradation efficiency which occurs within a time period of 180 min.

The sample synthesized for pH 10 calcined at 450 °C has high optical absorption and effective charge separation photo-generated carriers which enhance the photocatalytic activity. The percentage of degradation initially increases with increasing the pH values due to the increment in photonic efficiency whereas a further increase in pH value leads to lower degradation efficiency. The less photocatalytic behavior at pH 9 and 11 was due to the agglomeration of particles which reduces the surface to volume ratio and restricts the amount of incoming light radiation [45]. There was almost no significant variation in the crystallite size of the synthesized BiVO₄ nanoparticles. From the x-ray diffraction study, it was observed that more background radiation resulted.
from the samples synthesized at pH 9 and 11 which was an indication of higher native crystalline defects. These defects might be the cause for the poor photocatalytic activity which will act as traps/recombination centers for the excited charge carriers. The good crystallinity of the m-BiVO₄ nanoparticles at pH 10 enhances the light-harvesting properties by increasing the mobility of charge carriers which minimizes the defects [46] leading to
higher photocatalytic activity. The reason for the good photocatalytic degradation at pH 10 may be due to the predominant peak of (121) plane, narrow bandgap energy with less electron-hole pair generation leading to low recombination rate which enhances the photocatalytic activity.

The reaction kinetics between dye and catalyst is found by the Langmuir-Hinshelwood model

\[
 K_{app} t = \ln \frac{C}{C_0}
\]

where '\( K_{app} \)' is apparent rate constant, '\( C_0 \)' - initial concentration and '\( C \)' - final concentration of RhB and the concentration RhB at the reaction time '\( t \)', respectively. The kinetic plot (figure 9) and the inset table shows the regression analysis parameter rate constant and correlation coefficient (R²). It was observed that the apparent rate constant (0.094 min⁻¹) and coefficient value (0.9975) were found to be high for the BiVO₄ nanoparticles at pH 10 and the calculated correlation coefficient (R²) value approaches to 1 which shows photocatalytic behavior occurs in a linear fashion.
The photocatalytic degradation process of RhB dye under visible-light irradiation using BiVO₄ photocatalyst was given as schematic representation in figure 10. When visible-light irradiated on the catalyst surface, the electrons which were photogenerated migrates to the excited state due to the intramolecular transition (\(\pi \rightarrow \pi^*\)). The photogenerated electrons were impregnated into the conduction band of BiVO₄, leaving the RhB dye cation radicals. Furthermore, the photogenerated electrons present in the conduction band of BiVO₄ were trapped by O₂ molecules resulting in the generation of active species (O₂·⁻). Hence the reaction between RhB dye cation radicals and active species leads to the destruction of chromophore rings in the organic effluent.

In order to evaluate the reproducibility of the good photocatalyst (pH 10) as a precursor solution in RhB dye, the reusability test was examined under visible-light irradiation which was an important factor for the application related to the treatment of wastewater. The photocatalytic efficiency was predicted for four cycles successively. After each cycle, the photocatalyst was separated from the pollutants, washed with distilled water, dried and reused for the next cycle. From the obtained results, it was found that the photocatalytic activity does not exhibit any variation, confirming the sample stability during the photocatalytic reaction. The chemical stability of the photocatalyst was also confirmed by XRD (figure 11) indicating that m-BiVO₄ structure remains unchanged.

4. Conclusion

The effect of pH on BiVO₄ nanoparticles synthesized by the co-precipitation method was investigated. From the results, the microstructure of the synthesized BiVO₄ nanoparticles was significantly dependent on the pH. Efforts were focused on the changes in size and shape of the obtained BiVO₄ nanostructures when the volume ratios of NaOH were varied. The outcome of varying the pH shows a considerable effect on the photocatalytic performance under visible-light irradiation. The better photocatalytic degradation of RhB dye for prepared BiVO₄ nanoparticle at pH 10 shows good chemical stability and reusability. Thus the photocatalytic activity of BiVO₄ was increased under basic conditions than at acidic and neutral conditions. This toxic-free, environmentally friendly, cost-effective and simple co-precipitation method can also be used to synthesize other metal oxide material in the upcoming years.

ORCID iDs

C Ravi Dhas @ https://orcid.org/0000-0001-7529-5972

References

[1] Wu F, Li X, Liu W and Zhang S 2017 Applied Surface Science 405 60
[2] Tian Q, Yu X, Zhang L and Yu D 2017 Journal of Colloid and Interface Science 491 294
[3] Qin J, Zhang X, Yang C, Cao M, Ma M and Liu R 2017 Applied Surface Science 392 196
[4] Regmi C, Kshetri Y K, Ray S K, Pandey R P and Lee SW 2017 Applied Surface Science 392 61
[5] Long M, Cai W, Cai J, Zhou B, Chai X and Wu Y 2006 The Journal of Physical Chemistry B 110 20211
[6] Sierz V and Mason T 1 2009 Molecules 14 2284
[7] Niederberger M and Pinna N 2009 Metal Oxide Nanoparticles in Organic Solvents: Synthesis, Formation, Assembly and Application. (Dordrecht, Heidelberg London New York: Springer Science & Business Media) (https://doi.org/10.1007/978-1-4882-671-7)
[8] Kudo A, Ueda K, Kato H and Mikami I 1998 Catalysis Letters 53 229
[9] Sayama K, Nomura A, Arai T, Sugita T, Abe R, Yanagida M, Oi T, Iwasaki Y, Abe Y and Sugihara H 2006 The Journal of Physical Chemistry B 110 11352
[10] Yu J, Zhang Y and Kudo A 2009 Journal of Solid State Chemistry 182 223
[11] Xi G and Ye J 2010 Chemical Communications 46 1893
[12] Wang W, Yu Y, An T, Li G, Yip H Y, Yu J C and Wong P K 2012 Environmental Science & Technology 46 4599
[13] Zhao Z, Dai H, Deng J, Liu Y and Au C T 2013 Chinese Journal of Catalysis 34 1617
[14] Yin W, Wang W, Zhou L, Sun S and Zhang J 2010 Journal of Hazardous Materials 173 194
[15] Huang C M, Pan G-T, Peng P-Y and Yang T C-K 2010 Journal of Molecular Catalysis A: Chemical 327 38
[16] Martinez-de la Cruz A and Perez U G 2010 Materials Research Bulletin 45 135
[17] Pérez U G, Sepúlveda-Guzmán S, Martinez-de la Cruz A and Méndez U O 2011 Journal of Molecular Catalysis A: Chemical 335 169
[18] Liu W, Cao L, Su G, Liu H, Wang X and Zhang L 2010 Ultrasonics Sonochemistry 17 669
[19] Obregón S and Colón G 2013 Journal of Molecular Catalysis A: Chemical 376 40
[20] Liu W, Yu Y, Cao L, Su G, Liu X, Zhang L and Wang Y 2010 Journal of Hazardous Materials 181 1102
[21] Chung C-Y and Lu C-H 2010 Journal of Alloys and Compounds 502 L1
[22] Liu G, Zhao Y, Sun C, Li F, Lu G Q and Cheng H M 2008 Angewandte Chemie International Edition 47 4516
[23] Zhang A, Zhang J, Cui N, Tie X, An Y and Li L 2009 Journal of Molecular Catalysis A: Chemical 304 28
[24] Tan G, Zhang L, Ren H, Wei S, Huang J and Xia A 2013 ACS Applied Materials & Interfaces 5 5186
[25] Sun M, Guo P, Wang M and Ren F 2019 Optik 179 672
[26] Chiangraeng N, Chuachavalvituk A, Choklap W, Kaosuphong S and Nimmannpipup P 2019 Ferroelectrics 552 42
[27] Zhang A, Zhang J, Cui N, Tie X, An Y and Li L 2009 Journal of Molecular Catalysis A Chemical 304 28
[28] Dabodiya T S, Selvarsar P and Murugan A V 2019 Inorganic Chemistry 58 3096
[29] Ravidhas C, Josephine A J, Sudhagar P, Devadoss A, Terashima C, Nakata K, Fujishima A, Raj A M E and Sanjeeviraja C 2015 Materials Science in Semiconductor Processing 30 343
[30] Lei B-X, Zeng L-L, Zhang P, Sun Z-F, Sun W and Zhang X-X 2014 Advanced Powder Technology 25 946
[31] Dhas C R, Christy A J, Venkatesh R, Anuratha K, Ravichandran K, Raj A M E, Subramanian B and Panda S K 2017 Solar Energy 157 58
[32] Ravi Dhas C, Christy A J, Venkatesh R, Kirubakaran D D, Sivakumar R, Ravichandran K, Raj A M E and Sanjeeviraja C 2017 Materials Research Innovations 21 286
[33] Zhang Y, Li G, Yang X, Yang H, Lu Z and Chen R 2013 Journal of Alloys and Compounds 554 544
[34] Zheng Y, Liu Y, Zhou H, Huang W and Pu Z 2018 Journal of Alloys and Compounds 734 112
[35] Hardcastle F D, Ishihara H, Sharma R and Biris A S 2011 Journal of Materials Chemistry 21 6337
[36] Gotic M, Music S, Ivanda M, Soufek M and Popovic S 2005 Journal of Molecular Structure 744 535
[37] Zhang L, Wang W, Zhou L and Xu H 2007 Small 3 1618
[38] Liu S, Yin K, Ren W, Cheng B and Yu J 2012 Journal of Materials Chemistry 22 17759
[39] Chen L, Yin S-F, Huang R, Zhang Q, Luo S-L and Au C-T 2012 CrystEngComm 14 4217
[40] Karunakaran C, Kalaivani S and Vinayagamoorthy P 2014 Materials Letters 122 21
[41] Quintana-Melgoza J, Cruz-Reyes J and Avalos-Borja M 2001 Materials Letters 47 314
[42] Zawawi S M M, Yahya R, Hassan A, Mahmud H E and Daud M N 2013 Chemistry Central Journal 7 80
[43] Kudo A, Omori K and Kato H 1999 Journal of the American Chemical Society 121 11459
[44] Ravidhas C, Anitha B, Arivukarasan D, Venkatesh R, Christy A J, Jothivenkatachalam K, Nithya A, Raj A M E, Ravichandran K and Sanjeeviraja C 2016 Journal of Materials Science: Materials in Electronics 27 5020
[45] Dhas C R, Arivukarasan D, Venkatesh R, Josephine A J, Malar K M G, Monica S E S and Subramanian B 2019 Solid State Sciences 92 36
[46] Sivarajani K and Gopinath C S 2011 Journal of Materials Chemistry 21 2639
[47] Dhas C R, Venkatesh R, Jothivenkatachalam K, Nithya A, Benjamin B S, Raj A M E, Jeyadheepan K and Sanjeeviraja C 2015 Ceramics International 41 9301