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In the present study TiO2 nanotube arrays (TNTs) were loaded with a post-transition metal oxide particles namely SnO2 via incipient wet impregnation method by varying its concentration (1.59 wt%, 2.25 wt% and 2.84 wt%). The photocatalytic activity of the prepared photocatalyst was evaluated for the degradation of methylene blue (MB) in presence of natural solar light irradiation. The morphological analyses revealed that the prepared TNTs had average inner diameter of 109 nm, wall thickness of 15 nm and tube length of 7–10 μm, respectively, while the crystalline phase and raman spectra confirmed the 100% anatase mineral form of TiO2. Further, the presence of SnO2 in TNTs was confirmed by high resolution transmission electron microscopy (HRTEM) and X-ray photoelectron spectroscopy (XPS). The visible light absorption properties of TNTs improved drastically with increasing SnO2 loadings. The coupling effect of SnO2 and TiO2 significantly enhanced degradation efficiency of MB. An 84% degradation of MB was achieved in 6 h of irradiation under clear sky condition.

Keywords: TiO2 Nanotube Arrays, SnO2, Solar Light, Methylene Blue, Photodegradation.

1. INTRODUCTION

TiO2 is one of the most promising photocatalysts because of its high photocatalytic activity, stability, low cost and non toxic nature. Among TiO2 materials, self-organized and vertically oriented TNTs are of great interest due to their: (i) high surface-to-volume ratios, high surface area (ii) good charge transport properties and (iii) size dependent properties. These nanotubes are most widely used in the quantum dots-sensitized solar cells, carbon dioxide (CO2) reduction, dye degradation, dye-sensitized solar cells, photoelectrolysis and various biomedical applications. However, the photocatalytic activity is limited by its visible light utilization and high recombination rate of photogenerated electron–hole pairs due to its wide band gap (3.2 eV for anatase and 3.0 eV for rutile). They can be excited only with UV light irradiation (λ < 380 nm), which covers ~5% of the total solar spectrum. The researchers improved the photocatalytic activity of TiO2 in the visible light region by doping with metals (Cu, Pt, Fe, Pd, Ag, Ni) and non-metal elements such as nitrogen (N), boron (B), sulphur (S) and carbon (C) on its surface. The another alternative is to combine TiO2 with semiconductors such as SnO2, NiO, In2O3, WO3, Co3O4 and Cu2O. The addition/inclusion of such semiconductors can facilitate charge separation and extend the photo-responding range to the visible region.

Among those semiconductors, SnO2 is most suitable to couple with TiO2 due to its conduction band (Ecb = 0 V vs. NHE at pH 7) is lower than that of TiO2 (Ecb = −0.5 V vs. NHE at pH 7). The coupling allows the photoexcited electron transfer from TiO2 to conduction band of SnO2, leaving behind a positive hole on TiO2 and thereby hinder charge recombination and improve photocatalytic efficiency. Vinodgopal and Kamat (1995) demonstrated the principle of charge separation in a SnO2/TiO2 coupled semiconductor. In addition, they also reported the electrochemically assisted photocatalytic experiments using...
coupled SnO2/TiO2 semiconductor thin films in the degradation of textile dye effluent. Hou et al. (2007) prepared SnO2/TiO2 composite in hydrothermal condition with proper amount of SnO2 loading that showed an increase in photocatalytic activity for degradation of methylene blue.25 A bicomponent TiO2–SnO2 nanofiber photocatalyst prepared via electrospinning showed enhanced photocatalytic activity for the oxidation of RhB dye compared to pure TiO2 under UV light.24 The studies on the natural solar-light-driven photocatalytic activity are still limited, although very few studies on SnO2/TNTs catalysts have been reported. Most of them are widely used for lithium storage.25,26 In recent years, self organized and vertically oriented TNTs have been the focus of research8,15,21 due to their easy recovery and large surface area available for the photo reaction. Most suitably SnO2 could be the promising materials for such surface functionalization.

The present finding emphasizes on preparing TNTs with varied weight percentage of SnO2 via simple incipient wet impregnation method for higher visible light harvesting from solar spectrum. The photocatalytic activity of the SnO2/TNTs and pure TNTs were evaluated by degrading methylene blue (MB) dye under natural solar-light irradiation. The loading of nanosized SnO2 into TNTs possesses the following advantages:

1. The presence of Sn4+ species and surface defects extend the photo-responding range.
2. SnO2 nanoparticles play as an electron collector to facilitate rapid separation of photogenerated charges before recombination.
3. Aligned TNTs with a self-organized and self-supported array structure lead to high physical stability.

2. EXPERIMENTAL DETAILS

2.1. Preparation of SnO2/TNTs

All the chemical reagents were of analytical purity and purchased from Sigma-Aldrich Chemical Co. Self-organized TNTs layers were prepared directly on Ti foils (99.7%, Sigma-Aldrich) via electrochemical anodic oxidation in ethylene glycol (anhydrous, 99.8%) electrolyte containing 0.3 M ammonium fluoride (NH4F, 98%) and 2 vol% water (H2O) with graphite rod as the counter electrode under 50 V for 3 h. Ti foils (20 mm × 30 mm × 0.25 mm) were ultrasonically cleaned with acetone and ethanol prior to anodization. The anodized samples were rinsed thoroughly with DI water and then annealed at 450 °C for 1 h. The annealed samples were sonicated with ethanol for 30 min to remove the bundled impurities on top openings of the pores of the nanotubes. The loading of SnO2 onto TNTs were achieved by incipient wet impregnation method. The preparation steps followed were: The prepared TNTs samples were immersed overnight in SnCl2·5H2O aqueous solution. The molar concentration of SnCl2·5H2O aqueous solution was varied in a range of 0.5–2.5 M. This resulted in different concentration of SnO2/TNTs namely 1.59 Sn, 2.25 Sn and 2.84 Sn, respectively. The prepared samples were annealed at 450 °C for 2 h with the heating rate of 10 °C min−1 to induce crystallization. Similarly, a pure TNTs sample was prepared for comparison.

2.2. Characterization of SnO2/TNTs

The morphologies and composition of the samples were examined using a field emission scanning electron microscope (FESEM, Auriga, Zeiss) equipped with an EDS (energy dispersive X-ray spectroscopy) detector. The images were taken at an accelerating voltage of 20 kV. High resolution transmission electron microscope (HRTEM, Tecnai 20, Philips) images were obtained at 200 kV. The crystalline phase was identified using X-ray diffractometer (XRD, D8 Advance, Bruker). The target used in the diffractometer is copper (Cu Kα radiation, λ = 1.54 Å). The surface chemical composition of the samples was analyzed by X-ray photoelectron spectroscopy (XPS, Axis Ultra DLD, Kratos) with Al Kα radiation source. The binding energies were normalized to the signal for adventitious carbon at 284.6 eV. Light absorption properties were performed using UV-vis-NIR spectrophotometer (Lambda 750, Perkin Elmer) with a wavelength range of 200–800 nm. Raman spectroscopy was recorded on Raman spectrometer (RamanMicro 200, Perkin Elmer) with Raman shift range of 100–700 cm−1.

2.3. Photocatalytic Degradation of Methylene Blue (MB)

The solar-light-driven photocatalytic activity of SnO2/TNTs was evaluated by adopting methylene blue (MB) as model pollutant under solar light irradiation. The degradation of MB was carried out in a 1000 mL beaker with the working volume of 200 mL of MB solution (1.56 × 10−5 M). The prepared samples were loaded in MB solution with only one side faced to solar light irradiation. Prior to the photocatalytic experiment, the dark reaction was carried out for 30 min to achieve the adsorption equilibrium. The samples were collected at regular time interval and analyzed for residual MB concentration with visible spectrometer (Spectroquant® Pharo 100, Merck) at λmax = 664 nm. The drawn samples were dropped back into the beaker after the measurement to allow further degradation. The experiment was carried out at clear sky condition at University of Malaya, Kuala Lumpur (latitude 10° 15’ E and longitude 3° 17’ N) between 11.00 am and 5.00 pm in the months of May (2012). Solar light intensity was measured using LT Lutron LX-101 Lux meter of 1000 × 100 lux and the average light intensity over the duration of clear sky weather condition is found to be 97 220 lux (For solar light (AM 1.5), 100 mW/cm2 corresponds to approximately 120 000 lux).
3. RESULTS AND DISCUSSION

3.1. Structural and Morphological Characterization

Figures 1(A) and (B) show the surface and cross-sectional FESEM image of synthesized TNTs. The top surface image (Fig. 1(B)) shows that TNTs are well attached to each other and one-dimensional vertically oriented. The average inner diameter of these nanotubes is 109 nm, nanotube wall thickness is 15 nm and the tube length is in the range of 7–10 μm. The top view image of SnO$_2$/TNTs is shown in Figure 1(D). It is apparent that the morphological structure of TNTs was not affected by SnO$_2$ loading. Further, SnO$_2$/TNTs sample did not show significant morphological changes with increasing SnO$_2$ concentration (data not shown). The energy-dispersive X-ray spectroscopy (EDS) analysis (Fig. 1(C)) confirms the presence of Sn, Ti and O. The uniformity of SnO$_2$ dispersion was obtained via EDS analysis over different spots on the nanotubes cross section area with very reproducible peaks obtained, especially for Sn. Figure 2(A) shows that average crystallite size of SnO$_2$ nanoparticles less than 5 nm were distributed in TNTs surface. Direct evidence of crystalline nature of TiO$_2$ and SnO$_2$ was observed and is shown in Figures 2(A) (inset) and (B), respectively. Two lattice planes with spacing of 0.35 nm and 0.33 nm, corresponding to the (101) plane of anatase TiO$_2$ and (110) plane of SnO$_2$ was also observed clearly.\textsuperscript{38,39}

Figure 3(A) shows the XRD pattern for TNTs and SnO$_2$/TNTs. The diffraction peaks of all prepared samples are mainly ascribed to the peaks of TiO$_2$ anatase phase and Ti substrate. The Ti peak belongs to Ti foil substrate underneath the oxide nanostructure layer. No peak corresponding to TiO$_2$ rutile phase and SnO$_2$ was detected. It has been virtually no phase change in TiO$_2$ after the loading of SnO$_2$ nanoparticles. The evident peaks of tetragonal TiO$_2$ anatase phase (JCPDS no. 21-1272) are found at 25.3°, 36.9°, 37.8°, 48.0°, 53.9°, 55.1°, 62.7°, 68.8° and 75.0°, corresponding to (1 0 1), (1 0 3), (0 0 4), (2 0 0), (1 0 5), (2 1 1), (2 0 4), (1 1 6) and (2 1 5) crystal planes, respectively. The crystalline phase of SnO$_2$ could not be detected by XRD when TNTs were loaded with different concentration of SnO$_2$. It indicates that Sn cations (0.69 Å) are well substituted into the Ti cations (0.68 Å) in anatase TiO$_2$ lattice due to their similar ionic radii.\textsuperscript{40} In addition, this could be due to the presence of SnO$_2$ in low concentration and it is uniformly small and well dispersed on TiO$_2$ surface. Similar such observations were reported by Sakthivel et al. (2004)\textsuperscript{41} and Ku et al. (2011).\textsuperscript{42} The lattice parameters and crystallite size of all

![Figure 1](image-url)
samples are calculated using the formula stated below and are summarized in Table I. The average crystallite sizes of TiO$_2$ anatase were calculated using Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta}$$  \hspace{1cm} (1)$$

where $\beta$ is the full width half maximum (FWHM) for the $2\theta$ peak, $K$ is the shape factor taken as 0.89 for calculations, $\lambda$ is the wavelength of X-ray (0.154 nm), and $\theta$ is the diffraction angle. The lattice parameters were measured using (1 0 1) and (2 0 0) in anatase crystal planes by using Bragg’s equations:

$$d_{(h k l)} = \frac{\lambda}{2 \sin \theta}$$  \hspace{1cm} (2)$$

Formula for tetragonal system:

$$d_{(h k l)}^2 = h^2a^2 + k^2b^2 + l^2c^2$$  \hspace{1cm} (3)$$

As depicted in Table I, the lattice parameters and crystallite size of all samples decrease with increasing SnO$_2$ concentration. It can also be observed from Figure 3(B) that there is a shift of the (1 0 1) peak towards higher angles with increase in SnO$_2$ concentration, resulting in changes in the lattice parameters. In addition, the decrease in the (1 0 1) anatase peak intensity of SnO$_2$/TNTs in

<table>
<thead>
<tr>
<th>Sample</th>
<th>Crystallite size (nm)*</th>
<th>Cell parameters $a = b, c$ (Å)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNTs</td>
<td>34.50</td>
<td>3.7868, 9.5102</td>
</tr>
<tr>
<td>1.59 Sn</td>
<td>33.35</td>
<td>3.7863, 9.4308</td>
</tr>
<tr>
<td>2.84 Sn</td>
<td>25.00</td>
<td>3.7764, 9.3196</td>
</tr>
</tbody>
</table>

Notes: *Measured by Scherrer’s equation; *Estimated according to Eqs. (2) and (3).
The challenge in improving the properties of TiO$_2$ is to shift the absorption spectrum into the visible region to enable more efficient solar light harvesting. The diffuse reflectance spectra (DRS) of SnO$_2$/TNTs and pure TNTs samples are depicted in Figure 4. It can be seen that 1.59 Sn did not show a significant red-shifted absorption edge towards visible region due to its marginal increase in Sn concentration compared to that of TNTs. Meanwhile, the further increasing Sn concentration up to 2.25 wt% and 2.84 wt% results in a drastic shift towards the visible region. It is known that the doping energy level of Sn$^{4+}$ is located at 0.4 eV below the TiO$_2$ conduction band.\(^{44}\) Hence, the visible light absorption of SnO$_2$/TNTs can be attributed to the charge-transfer transitions between Sn$^{4+}$ electrons and the TiO$_2$ conduction band.\(^{45}\) In addition, the presence of Ti$^{3+}$ species which is observed by XPS on SnO$_2$/TNTs (Fig. 6(D)) can induce oxygen vacancy states between the valence and conduction band, which could also contribute to the visible response\(^{46}\) and electron–hole pairs separation.\(^{47}\) The obtained band gap energy through Tauc plot (figure not shown) are 3.09 eV, 3.05 eV and 2.97 eV for TNTs, 1.59 Sn and 2.25 Sn, respectively. The Tauc plot is a plot of $(F(R) \cdot h\nu)^{1/2}$ against $h\nu$, where $F(R)$ is the Kubelka-Munck function derived from $F(R) = (1 - R)^2/2R$ the photon energy. The band gap energies can be determined by extrapolating the maximum slope of the curve to the photon energy axis (x-axis).

### 3.3. Raman Shift Spectra

Figure 5 depicts the Raman shift spectra of the prepared samples. The Raman peaks for both pure TNTs and SnO$_2$/TNTs at 144, 197, 399, 519 and 639 cm$^{-1}$ are assigned to $E_g(1)$, $E_g(2)$, $B_1g(1)$, $A_1$g, $B_1g(2)$ and $E_g(3)$ active modes of the anatase phase, respectively.\(^{48}\) This result is consistent with crystallographic patterns and confirms the formation of a bulk anatase phase after annealing treatment. No peaks related to SnO$_2$ or other oxidation state of Sn was detected in the spectra of SnO$_2$/TNTs samples. This specifies the high dispersion of SnO$_2$ on TiO$_2$ surface,\(^{49}\) which corresponds to the XRD results. The SnO$_2$/TNTs sample shows that $E_g$ mode of anatase (144 cm$^{-1}$) (Fig. 5) decreases in intensity, becomes broader and red shifted to higher frequency region. Besides, few broader peaks also can be observed at 399, 519 and 639 cm$^{-1}$ in SnO$_2$/TNTs sample. This phenomenon is due to the breakdown of long-range translational crystal symmetry which is caused by the Sn$^{4+}$ substitution defects.\(^{50}\)

### 3.4. XPS Analysis

High-resolution XPS was performed to determine the chemical composition and the oxidation state for SnO$_2$/TNTs samples. The fully scanned XPS spectra (Fig. 6(A)) indicate that Ti, O, C and Sn elements exist in SnO$_2$/TNTs samples. XPS of Sn 3d, O 1s and Ti 2p core levels of the SnO$_2$/TNTs exist as: (1) Ti 2p region (450–470 eV); (2) Sn 3d region (480–500 eV); and (3) O 1s region (520–540 eV). Peak fitting to the spectra was applied using Gaussian-Lorentzian peak shape after subtraction.
of Shirley background. The C element can be ascribed to the adventitious carbon based contaminant from the XPS instrument and the binding energy of C 1s peak at 284.6 eV is used as internal charge correction. As shown in Figure 6(B), high-resolution XPS of O 1s core level can be fitted to three kinds of chemical states. The peaks at 529.9, 531.3 and 532.8 eV can be assigned to crystal lattice oxygen of Ti–O, Sn–O and adsorbed water, respectively. As shown in Figure 6(C), the Sn 3d peak is found at 486.1 eV and the Sn 3d peak is located at 494.5 eV. The splitting of Sn 3d doublet at 8.41 eV confirmed the valence state of Sn is +4.

As shown in Figure 6(D), there are two peaks observed at 458.1 eV (Ti 2p1/2) and 463.9 eV (Ti 2p3/2), both correspond to Ti4+. The nonstoichiometric nature of TiO2 (Ti4+) surface was proved by the presence of TiO (Ti2+) and Ti2O3 (Ti3+) peaks. The presence of Ti4+ can be detected at peak 460 eV. The two shoulder like peaks in the lower binding energy on Ti 2p3/2 (456.9 eV) and Ti 2p1/2 (462.2 eV) are assigned to Ti3+ which are generated from the substitution of Ti4+ (0.68 Å) by Sn4+ (0.69 Å) with similar ionic radii, leading to stoichiometry changes in TiO2 lattice. Interestingly, the binding energies for Ti 2p1/2 and Ti 2p3/2 shifted towards lower side with the substitution of Sn4+ compared to pure TNTs (Fig. 6(D)). This phenomenon can be correlated to the existence of Ti with lower valence (Ti3+, Ti4+) due to formation of oxygen vacancies after SnO2 loading.31 These XPS results also in agreement with XRD results (Fig. 3(B)) which show SnO2/TNTs samples shift to higher angle compared to that of TNTs. Both results confirm that SnO2 is successfully loaded in TiO2 lattice in substitution mode and accompanied by oxygen vacancy formation.

3.5. Photocatalytic Activity SnO2/TNTs

Methylene blue (MB) was used as the model pollutant to evaluate the photocatalytic activity of the SnO2/TNTs. Figure 7(B) shows the solar-light-driven photocatalytic activity for the degradation of MB over all prepared photocatalysts at clear sky condition. The initial concentration (C0) is the MB concentration after adsorption–desorption equilibrium. Regardless of SnO2 concentration, 40.1 to 40.7% of the dye were removed under dark condition for 30 min before exposure to solar irradiation. Since the photocatalytic principles also depend on the surface phenomena, this good adsorption property can further enhance the photodegradation in the presence of light source. The photocatalytic reactions for all samples followed pseudo first-order reaction kinetics, which is expressed by equation:

$$\ln \left( \frac{C_0}{C} \right) = kt$$

where k is the first-order reaction constant, C0 and C are the initial and the reaction concentrations of the MB dye, respectively. The kinetic plot and photocatalytic results are given in Figure 7(A) and Table II, respectively. Regardless
of SnO$_2$ concentration, all SnO$_2$/TNTs photocatalysts showed higher degradation efficiency than pure TNTs. In the initial reaction, the solar-light-driven activity of SnO$_2$/TNTs samples with lower concentration (1.59 wt% and 2.25 wt%) increased with increase in SnO$_2$ concentration. After 210 min of reaction time, solar-light-driven activity of 1.59 Sn and 2.25 Sn started to slow down and reached identical MB degradation (84%) towards the end. However, the photocatalytic activity decreased with increasing SnO$_2$ concentration up to 2.84 wt%. This is due to SnO$_2$ deposition on TNTs can form a space charge layer, which can separate the photoinduced electron–hole pairs. As the concentration of SnO$_2$ increases, the surface barriers become higher and the electron–hole pairs within the region are efficiently separated by the large electric field. But when in excess, the existence of SnO$_2$ particles on the TiO$_2$ surface blocks the active sites of TiO$_2$ and lessens the adsorption of reactant. It can also become the recombination centers of photoinduced electron–hole pairs and thereby decrease the photocatalytic activity. Furthermore, the charge-transfer transitions between Sn$^{4+}$ electrons and TiO$_2$ conduction band$^{39}$ promotes absorption edge in visible region. Finally, substitution of Ti$^{4+}$ by Sn$^{4+}$ can cause a lattice deformation and produce defects such as Ti$^{3+}$ and oxygen vacancy in the crystal. These defects can extend the absorption edge to visible region.$^{53,54}$ A competitive adsorption on the active sites between the reactant and the intermediate products could reduce the degradation rate towards the end of reaction.$^{55}$ Hence, the accessibility of reactant to the active sites is affected and resulting a non-significant difference of degradation efficiency for all SnO$_2$/TNTs when the reactions end. But indeed, as shown in Figure 7(A), there is still a difference in the kinetic rates for different concentration of SnO$_2$/TNTs.

### 3.6. Degradation Mechanism

The degradation mechanism of MB over SnO$_2$/TNTs is illustrated in Figure 8. It is well known that conduction band electrons ($e^-$) and valence band holes ($h^+$) are generated when TiO$_2$ is irradiated with light energy greater than its band gap (3.2 eV). As indicated in Raman and XRD results, Sn$^{4+}$ ions are incorporated in TiO$_2$ lattice in substitution mode. It creates Sn$^{4+}$ doping energy level which is located at 0.4 eV below the conduction band.$^{44}$ The excited electrons transfer from valence band to Sn$^{4+}$ doping energy level. The excited electron at the conduction band can also fall into Sn$^{4+}$ doping energy level.$^{56}$ The photogenerated electrons can also transfer from conduction band to SnO$_2$ nanoparticles since the conduction band of SnO$_2$ ($E_{CB} = 0$ V) is lower than that of the TiO$_2$ ($E_{CB} = -0.5$ V).$^{33}$

![Figure 8. Schematic diagram of charge transfer in SnO$_2$/TNTs photocatalyst under solar light irradiation.](image)

### Table II. Photodegradation of MB dye for TNTs and SnO$_2$/TNTs under solar light irradiation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>MB degraded (C$_0$ − C)/C$_0$ (%)</th>
<th>$K_b$ (min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNTs</td>
<td>65.4</td>
<td>0.003</td>
</tr>
<tr>
<td>1.59 Sn</td>
<td>84.0</td>
<td>0.005</td>
</tr>
<tr>
<td>2.25 Sn</td>
<td>84.2</td>
<td>0.005</td>
</tr>
<tr>
<td>2.84 Sn</td>
<td>84.0</td>
<td>0.005</td>
</tr>
</tbody>
</table>

**Notes:** $^a$After reaction for 6 h; $^b$Apparent rate constant deduced from linear fitting of ln(C$_0$/C) versus reaction time.
The photogenerated electrons at Sn$^{4+}$ doping energy level, TiO$_2$ conduction band and SnO$_2$ conduction band react with O$_2$ adsorbed on TiO$_2$ surface or dissolved oxygen in water to produce superoxide radical anion $O_2^-$.

While the photogenerated holes move from SnO$_2$ valence band to TiO$_2$ valence band. It oxidize the organic molecule in MB solution to form $R^+$, or react with OH$^-$ or H$_2$O then oxidizing them into •OH radicals. Ti$_3^+$ which is the surface defects as identified in XPS analysis can easily react with O$_2$ adsorbed on TiO$_2$ surface, leading to the formation of radicals such as $O_2^-$, HO$_2^-$, and •OH radicals. The resulting •OH radicals are strong oxidizing agent (standard redox potential +2.8 V) can oxidize MB dye to mineral end-products.

4. CONCLUSIONS

Self-organized and vertically oriented TNTs were loaded with SnO$_2$ particles using simple incipient wet impregnation method. The characterization results indicated that the morphology structure and crystalline phase of TNTs was not affected by the loading of SnO$_2$. The SnO$_2$/TNTs samples possess better visible light absorption property compared to that of TNTs. Overall, SnO$_2$/TNTs exhibited higher solar-light-driven photocatalytic activity than TNTs due to the contribution of substitutionally Sn$^{4+}$, surface defects (Ti$_3^+$ and oxygen vacancy) and SnO$_2$ nanoparticles. The factor to enhance solar-light-driven photocatalytic activity does not always depend on the good visible light absorption property. It also depends on the effective combination of the surface transfer of photoinduced charge-carriers and further dosage optimizing of SnO$_2$ nanoparticles to avoid electron–hole pairs recombination.

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References and Notes


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