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# Enhanced Visible Light Photoelectrochemical Performances with Nitrogen Doped TiO<sub>2</sub> Nanowire Arrays

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**Abstract:** Self-organized anodic anatase TiO<sub>2</sub> nanowire arrays doped with nitrogen have been successfully fabricated and their photoelectrochemical (PEC) properties have been characterized and found to be substantially improved compared to undoped nanowires or commercial P25 nanoparticles. Photocurrent measured with monochromatic incident light showed that the incident photon-to-current efficiency (IPCE, %) values of nanowire array electrodes with or without N-doping were obviously higher than that of commercial P25 nanoparticle electrodes, and nitrogen-doped TiO<sub>2</sub> nanowire arrays (NTNA) had noticeable absorption in the visible region. The NTNA electrodes showed the highest photocurrent density and power conversion efficiency under 100 mW/cm<sup>2</sup> visible light illumination. A maximum photoconversion efficiency of 0.52% was achieved for the NTNA sample at an applied potential of 0.09 V versus Ag/AgCl (saturated KCl) electrode under visible illumination, much higher than that of the undoped nanowire and commercial P25 nanoparticle electrodes. These results demonstrate that NTNA thin films are promising for enhancing the photoresponse and effectively improving PEC performances of nanostructured TiO<sub>2</sub> in the visible region for different applications including solar hydrogen generation.

**Key words:** nitrogen doped; TiO<sub>2</sub> nanowire arrays; visible light; photoelectrochemical performances; photocatalysis

**CLC Number:** TB383

**Document Code:** A

TiO<sub>2</sub> as a wide bandgap n-type metal oxide semiconductor has been extensively investigated for water splitting due to its good stability, nontoxicity, low cost, and high catalytic activity<sup>[1-3]</sup>. Recently, there have been extensive studies on nanostructured TiO<sub>2</sub>, such as nanotubes, nanowires and nanorods, as the electron transport materials due to their unique physical properties and wide range of applications<sup>[4-6]</sup>.

Compared to nanoparticles, one dimensional (1D) nanostructures such as nanowires and nanorods have better charge transport properties while, in the meantime, they have larger surface area in comparison to bulk or two dimensional (2D) nanostructures. Thus, TiO<sub>2</sub> nanowires and nanorods are considered as highly desired structures for both photovoltaic and photoelectrochemical applications. Different strategies have

been developed for synthesizing TiO<sub>2</sub> nanowires and nanorods, including sol-gel<sup>[7]</sup>, chemical vapor deposition (CVD)<sup>[8]</sup>, solvothermal method<sup>[9]</sup>, anodization<sup>[10]</sup> and glancing angle deposition (GLAD)<sup>[11]</sup>. Among these strategies, electrochemical anodization is relatively simple and provides a facile and direct approach for producing TiO<sub>2</sub> nanowires with high surface area and long wire length<sup>[10]</sup>.

Despite the promising properties of TiO<sub>2</sub> nanowires mentioned above, the wide bandgap of TiO<sub>2</sub> (3.0 eV for rutile and 3.2 eV for anatase) limits its photoresponse mainly to the UV region, which accounts for only ~ 5% of solar spectrum energy. Much effort has been made to narrow the effective bandgap of TiO<sub>2</sub> while maintaining its superior charge transfer and transport properties and photocorrosion stability. It has been shown that nitrogen-doping (N-doping) is an effective method to narrow the bandgap of anatase TiO<sub>2</sub> and thereby increase the visible light absorption<sup>[12-14]</sup>. For example, N-doping of TiO<sub>2</sub> nanotubes has been demonstrated using pure NH<sub>3</sub><sup>[15]</sup>. TiO<sub>2</sub> nanowire arrays (TNA), especially when doped with N, are considered as promising for photoelectrochemical applications because of the combination of expected enhanced visible absorption and better charge transport along long nano wire. However, to date the study of TNA or N-doped TiO<sub>2</sub> nanowire arrays (NTNA) has been very limited.

In the present work, N-doped self-organized anodic TiO<sub>2</sub> nanowire arrays (NTNA) have been fabricated using a simple electrochemical approach. Optical and photoelectrochemical studies have shown that the NTNA electrodes had substantially enhanced visible light photoresponse and improved photoconversion efficiency compared to TNA and nanoparticle electrodes. These improved properties are expected to be useful in applications including solar energy conversion, water splitting for hydrogen generation, as well as photoelectrochemical degradation of pollutants.

## 1 Experimental Section

### 1.1 Preparation of TiO<sub>2</sub> Nanowire Arrays

TiO<sub>2</sub> nanowire arrays (TNA) were prepared by a

modified method developed by Choi et al<sup>[10]</sup>. Typically, the polished Ti foil (0.25 mm thick, 99.38% purity, from Beijing General Research Institute for Nonferrous Metals) was pretreated by rinsing in an ultrasonic bath of acetone, alcohol and deionized water for 5 min in turn, then chemically etched by immersing in a mixture solution of HF, HNO<sub>3</sub> and H<sub>2</sub>O acids in the ratio of 1:4:5 (by Vol) for 30 s, rinsed in an ultrasonic bath of acetone, isopropanol and methyl alcohol for 5 min in turn, and finally rinsed in deionized water. At the end, the obtained substrate was dried with N<sub>2</sub> at room temperature.

The anodization process was carried out at room temperature using a direct current power supply (Dahua Wireless Instrument Co., Beijing) in a two-electrode electrolytic cell, with the pretreated Ti foil serving as the anode and Pt foil serving as the cathode. The anodizing voltage increased gradually from 0 to 50 V with an increasing rate of 100 mV/s and was then kept at 50 V for 10 h. The electrolyte was 15 mL of ethylene glycol (EG) solution containing NH<sub>4</sub>F (0.25%, by mass) and 500 μL deionized water. Generally, a small amount of water in the EG solution is essential for the formation of anodic TiO<sub>2</sub> nanowires at a high potential. After the anodization, the obtained substrate was immediately rinsed with deionized water and dried with a N<sub>2</sub> stream. Then, the anodized substrate was annealed at 450 °C in oxygen for 3 h with the cooling rate of 2 °C·min<sup>-1</sup> to convert the amorphous phase to the anatase crystalline phase.

The process of introducing the nitrogen dopant was carried out in a tube furnace. The obtained TiO<sub>2</sub> nanowires were immersed in 0.5 mol·L<sup>-1</sup> hexamethylenetetramine (HMT) solution for two days. Subsequently, the specimens were put in quartz tube, and the dopant was carried out by tube furnace at 400 °C for 1 h where N<sub>2</sub> acted as the carrier gas. After heating, the sample remained in the furnace until natural cooling down to room temperature.

### 1.2 Characterization

Powder X-ray diffraction (XRD) was performed

on a Bruker D8-Advance X-ray powder diffractometer with monochromatized K $\alpha$  radiation ( $\lambda = 0.15406$  nm). The  $2\theta$  range used in the measurements was from  $20^\circ$  to  $80^\circ$ . X-ray photoelectron spectroscopy (XPS) studies of the films were carried out on an X-ray photoelectron spectrometer (PHI Quantera SXM) using a non-monochromatized Al K $\alpha$  X-ray source (1486.6 eV). The energy resolution of the spectrometer was set at 0.5 eV, and the binding energy was calibrated using a C 1s (284.6 eV) spectrum of a hydrocarbon that remained in the XPS analysis chamber as a contaminant. SEM images were acquired on a field emission (FE) scanning electron microscope (JEOL JSM-7401F) operated at 3.0 kV. Mott-Schottky (MS) spectra were measured with a three-electrode cell, using the TiO $_2$ -based samples as the working electrode, a platinum wire as the counter electrode, and a standard Ag/AgCl in saturated KCl as the reference electrode. The electrolyte was 0.1 mol  $\cdot$  L $^{-1}$  KNO $_3$  aqueous solution. Mott-Schottky (MS) spectra were obtained with a PARSTAT-2273 Advanced Electrochemical System (Princeton Applied Research) controlled by a computer.

### 1.3 Photoelectrochemical Measurements

Photocurrent action spectra were measured in a two-electrode configuration, home-built experimental system, where the sintered TiO $_2$  photoanode served as the working electrode with an active area of about 1 cm $^2$  defined using Teflon tape and a platinum wire was used as the counter electrode. The generated photocurrent signal was collected by using a lock-in amplifier (Stanford Instrument SR830 DSP) synchronized with a light chopper (Stanford Instrument SR540). Photocurrent density vs bias potential characteristic was conducted with a three-electrode cell, using the sintered photoanode as the working electrode, a platinum wire as the counter electrode, and a standard Ag/AgCl in saturated KCl as the reference electrode. Photocurrent density vs bias potential characteristic spectra was obtained with a PARSTAT-2273 Advanced Electrochemical System (Princeton Applied Research) controlled by a computer. A 500 W Xe lamp with a monochromator and equipped with

AMOL1.5 filter (filter off lights with wavelength shorter than 400 nm for 100 mW/cm $^2$  visible light measurements) respectively, was used as the light source. The electrolyte was 0.1 mol  $\cdot$  L $^{-1}$  KNO $_3$  aqueous solution. All measurements were carried out after bubbling N $_2$  for 20 min and controlled automatically by a computer.

## 2 Results and Discussion

### 2.1 Structural Properties of Nitrogen Doped TiO $_2$ Nanowire Arrays

Figure 1 shows typical FESEM images of the morphologies of TNA and NTNA. As shown in Figure 1a, the TiO $_2$  nanowires were more than 10  $\mu$ m in length and 60 nm in diameter, and there remained the TiO $_2$  nanotubes with a diameter of about 100 nm underneath the nanowires. Figures 1b and c show different magnifications of TNA. Figure 1d shows that, after nitrogen doping, the morphologies of TNA did not obviously change, indicating that the N-doping process had little effect on the nanostructures of the as-prepared TNA. The morphologies of the TNA at low magnification were just like blooming flowers (Figures 1b and 1c), which seemed to follow the bamboo-splitting nanowire formation model<sup>[10]</sup>, i.e., highly organized TiO $_2$  nanotubes firstly formed in Ti foil at the beginning of the anodization, and the nanotubes were then vertically split off into several parts by the electric-field-directed etching. The splitting led to the formation of NTNA on the entire TiO $_2$  nanotube arrays.

Figure 2 shows the XRD patterns of fabricated TNA, NTNA and Ti foil. According to the XRD results, the diffraction peaks of Ti foil could be indexed into hexagonal phase (ICDD-JCPDS No. 44-1294). The diffraction peaks of TNA shown in curve b in Figure 2 could be indexed into anatase phase (ICDD-JCPDS No. 21-1272). As shown in curve c in Figure 2, the peaks of N-doped TNA showed no obvious change compared with those of TNA, which means the N-doping process did not change the phase of TNA.

The N - bonding information and the effect of

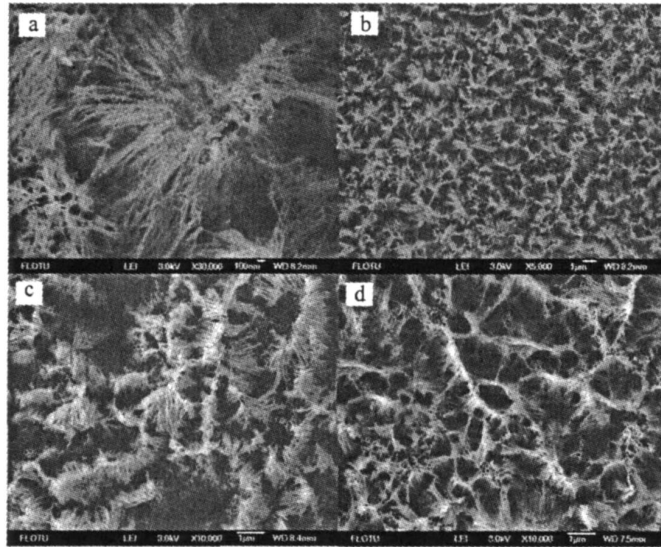


Fig 1 FE-SEM images of (a), (b) and (c) different magnified  $\text{TiO}_2$  nanowire arrays, (d) N-doped  $\text{TiO}_2$  nanowire arrays

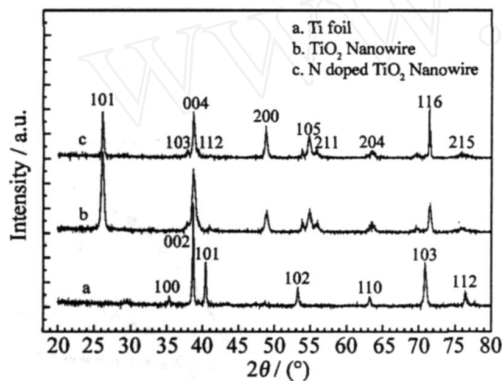


Fig 2 XRD patterns of (a) Ti foil, (b)  $\text{TiO}_2$  nanowires and (c) N doped  $\text{TiO}_2$  nanowires

nitrogen doping on the optical properties of NTNA were identified by the XPS technique. From Figure 3a, it can be seen that the NTNA contained Ti, O, N and C, and the binding energies of Ti 2p, O 1s, C 1s, and N 1s were 459.7 eV, 530.2 eV, 400.2 eV and 284.9 eV, respectively. Figure 3b shows the XPS spectra of only the nitrogen binding energies from 396 eV to 412 eV with three peaks at 398.7 eV, 400.2 eV and 405 eV, respectively. The XPS spectra of Ti 2p<sub>3/2</sub> and O 1s peaks are shown in Figure 3c, which verified the substitution of N for O in  $\text{TiO}_2$  crystals<sup>[16]</sup>.

As Figure 3b shows, the peak at 400.2 eV corresponds to molecularly chemisorbed nitrogen ( $\text{N}_2$ )

at the surface<sup>[14,17]</sup> or N atoms from N—N, N—H, O—N or N-containing organic compound absorbed on the surface<sup>[13]</sup>. It has been reported that the N 1s features appearing above 400 eV is due to Ti—O—N linkage<sup>[18]</sup>, suggesting that some nitrogen atoms were doped in the interstitial sites of TNA lattices. In addition, the intense peak at 405.3 eV could be originated from nitrite ions<sup>[19]</sup>, and the peak at 398.7 eV was assigned to nitrogen atoms which substituted for O and doped into the crystal lattices of nanowires to form the Ti—N bonds<sup>[20-21]</sup>.

As for the Ti 2p<sub>3/2</sub>, a peak is located at 458.9 eV for NTNA (Figure 3c), which was significantly lower than that of P25  $\text{TiO}_2$  powders (459.7 eV)<sup>[22]</sup> and  $\text{TiO}_2$  nanowires (459.3 eV)<sup>[17]</sup>, also indicating the nitrogen incorporation into the TNA. And the Ti 2p<sub>1/2</sub> at 463.5 eV peak was characteristic of the  $\text{Ti}^{\text{IV}}$  oxidation state<sup>[17]</sup>. The lower binding energy of Ti 2p<sub>3/2</sub> in the NTNA showed that the electronic interaction of Ti with anions was significantly different from that of  $\text{TiO}_2$  nanoparticles and nanowires, where the interaction was between Ti and O rather than N. It is known that the lower electron negativity of nitrogen compared with that of oxygen resulted in a decrease in percent ionicity and electron density around the N anion, causing the increase of the Ti electron density<sup>[22]</sup>.

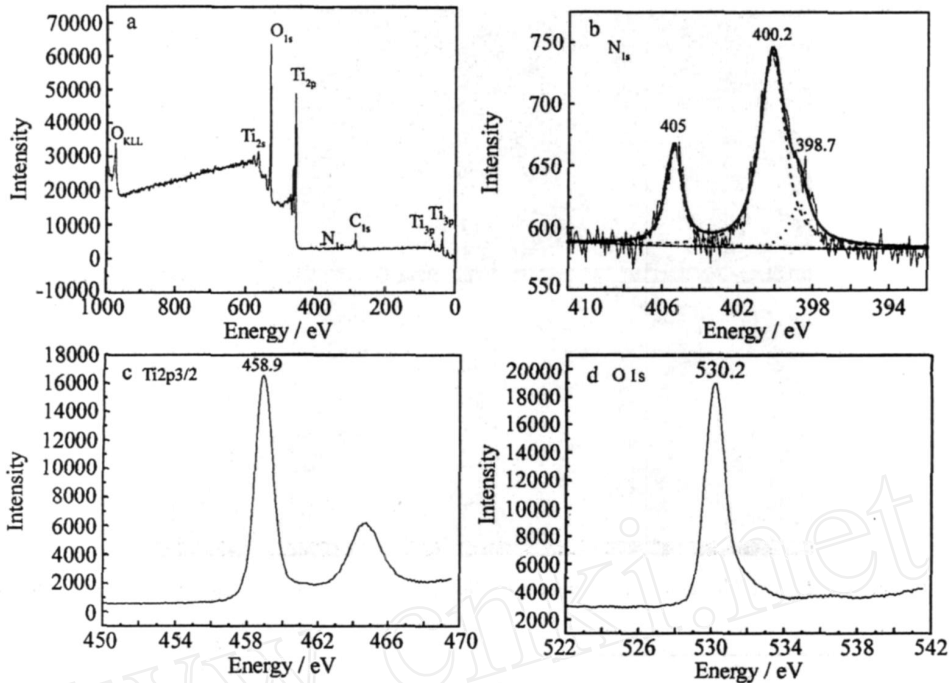


Fig 3 XPS spectra of N-doped  $\text{TiO}_2$  nanowires a elemental survey, b N 1s, c Ti  $2p_{3/2}$ , d O 1s

The O 1s peak appeared at around 530.2 eV corresponding to Ti—O in Figure 3d, which was similar to that for the  $\text{TiO}_2$  nanowires<sup>[17]</sup>, indicating that there was no discernible change in the chemical environment for oxygen. In addition, broadening on the higher bonding energy band for N- $\text{TiO}_2$  at 531.4 eV could be found. The appearance of this additional peak was attributed to the nitridation process. This feature was previously assigned to the presence of another kind of oxygen in N- $\text{TiO}_2$ <sup>[22]</sup>. On the basis of the above results and analysis, XPS results indicate that N doping into the crystal mainly results in Ti—N or N—Ti—O bonding.

## 2.2 Mott-Schottky (MS) Studies

Figure 4 shows Mott-Schottky (MS) measurement results, which were used to determine the difference in electronic properties of the TNA electrodes with or without N-doping<sup>[23-24]</sup>. As is clear from Figure 4, reversed sigmoidal plots were observed with an overall shape consistent with that typical for n-type semiconductors; And the reproducible flat-band potentials could be obtained from the intercepts of the linear region<sup>[25]</sup>. TNA electrodes showed a large

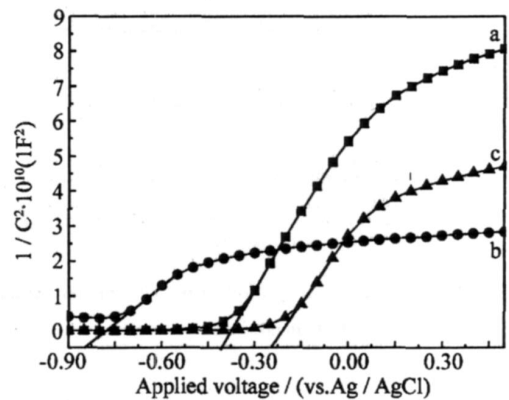


Fig 4 Mott-Schottky plots of for P25 nanoparticle films (a),  $\text{TiO}_2$  nanowires (b) and N-doped nanowires (c) electrodes. Mott-Schottky measurements were done at the frequency of 1 kHz in the aqueous solution of 0.1 mol  $\cdot \text{L}^{-1}$   $\text{KNO}_3$ , pH 7.5

positive shift of the conduction band as compared with the P25 nanoparticle electrodes, and NTNA had more positive flat-band potential than TNA electrodes.

It is well known that the presence of a large number of surface states can lead to a considerable change of the band position<sup>[26]</sup>. In most cases, a large number of surface states or oxygen vacancies are present in the P25  $\text{TiO}_2$  nanoparticles, whereas  $\text{TiO}_2$

nanowire structures have a lower density of surface states or oxygen vacancies that can lead to a change of the band position. Furthermore, in the case of NTNA, N atoms could substitute for some oxygen vacancies and reduce the recombination centers of charge carriers, leading to the much higher photocurrent density observed in comparison to the P25 nanoparticles. Mott-Schottky results show that the NTNA electrodes have lower density of surface states and thereby improve charge transport properties, which are useful for enhancing photocurrent density.

### 2.3 Photoelectrochemical Characterization

Photocurrent measurements with monochromatic incident light of P25 TiO<sub>2</sub> nanoparticles and TNA with and without N-doping were performed without bias in a two-electrode configuration. The illumination area of the photoanode was about 0.12 cm<sup>2</sup>. The incident photon-to-current efficiency (IPCE) was calculated using the following equation<sup>[31]</sup>:

$$\text{IPCE} / \% = \frac{(1240 \text{ eV} \cdot \text{nm}) (\text{photocurrent density } \mu\text{A} / \text{cm}^2)}{(\text{nm}) (\text{irradiance } \mu\text{W} / \text{cm}^2)} \times 100 \quad (1)$$

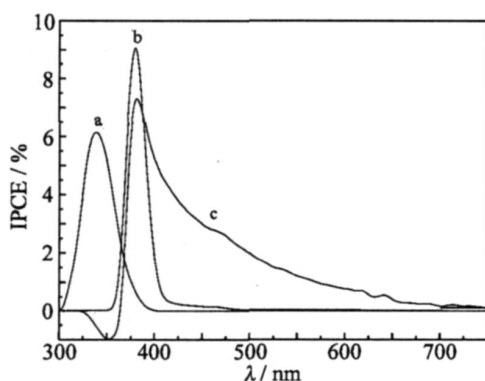


Fig 5 Incident photon-to-current efficiency (IPCE) spectra with monochromatic light at different wavelengths of P25 nanoparticles (a), TiO<sub>2</sub> nanowires (b) and N-doped TiO<sub>2</sub> nanowires (c) as photoanodes in 0.1 mol · L<sup>-1</sup> KNO<sub>3</sub> solution under Xe lamp irradiation

As shown in Figure 5, the maximum IPCE (%) values of NTNA and TNA electrodes reached 7.2%

and 9% at 380 nm, respectively, obviously higher than 4% measured for P25 TiO<sub>2</sub> thin film electrodes at 340 nm. The NTNA electrodes also showed noticeably higher photocurrent in the visible region, extending all the way to about 675 nm. In contrast, the undoped TNA and TiO<sub>2</sub> nanoparticles exhibited little or no photoresponse in the visible region. NTNA and TNA electrodes showed an apparent photocurrent maximum at about 380 nm, while the P25 TiO<sub>2</sub> layer electrodes showed a photocurrent maximum at about 340 nm. The positions of the photocurrent maximum are likely related to bandgap as well as the effective light absorption and scattering of the nanostructure films. The bandgap of anatase TiO<sub>2</sub> is at 387 nm or 3.2 eV<sup>[14]</sup>.

The higher IPCE (%) values of NTNA and TNA than P25 TiO<sub>2</sub> nanoparticle electrodes could be attributed to the different space charge layer within the wire wall<sup>[27]</sup>. Compared to random structures, the ordered nanowire array structures could also allow for reduced scattering and enhanced photoabsorption<sup>[28]</sup>, similar to photonic crystals or gratings. In addition, the higher crystallinity of TiO<sub>2</sub> nanowires could also enable more efficient electron injection and transport within the array electrodes, leading to longer electron lifetime and diffusion length in TiO<sub>2</sub> nanowires compared to nanoparticles<sup>[29]</sup>. It is clear that N doping is an effective way to improve the visible absorption of anatase TiO<sub>2</sub> by decreasing the effective TiO<sub>2</sub> bandgap with N-TiO<sub>2</sub> as a result of either mixing O2p states with its 2p states<sup>[31]</sup> or creating isolated N2p states above the valence band maximum of TiO<sub>2</sub><sup>[30-31]</sup>. And nitrogen doping into TiO<sub>2</sub> substituted oxygen and decreased the surface oxygen concentration in TiO<sub>2</sub> crystalline structure leading to lower maximum peak of IPCE of NTNA than that of TNA.

Figure 6 shows that the photocurrent density as a function of applied potentials for the NTNA, TNA and P25 electrodes in 0.1 mol · L<sup>-1</sup> KNO<sub>3</sub> solution under 100 mW / cm<sup>2</sup> visible light irradiation. The dark current density was found to be negligible, and the photocurrent density of nanoparticle electrodes was very low in the visible. However, the photocurrent densi-

ties of the NTNA and TNA electrodes were much higher in the visible; and, furthermore, the photocurrent density of the NTNA electrodes was about three times as much as that of the TNA electrodes. Considering the results in Figure 4, this result is consistent with the expectation of enhanced photocurrent density for the NTNA electrodes.

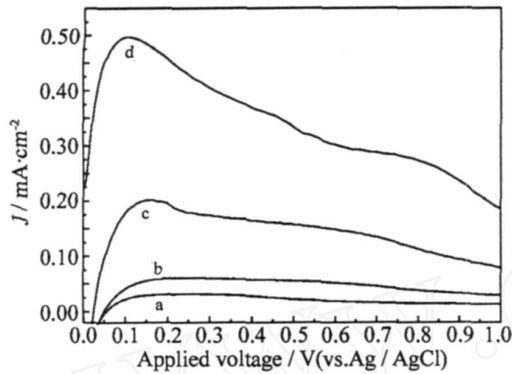


Fig 6 Variation of photocurrent density vs bias potential for P25 nanoparticle films (b), TiO<sub>2</sub> nanowires (c) and N-doped TiO<sub>2</sub> nanowires (d) in 0.1 mol · L<sup>-1</sup> KNO<sub>3</sub> solution under visible light illumination

The photoconversion efficiency of light energy to chemical energy in the presence of an external applied potential could be calculated according to the following equation<sup>[32]</sup>:

$$(\%) = \frac{(\text{total power output} - \text{electrical power input})}{\text{light power input}} \times 100 = j \frac{(E_{\text{rev}}^0 - |E_{\text{app}}|)}{I_0} \times 100 \quad (2)$$

where  $j$  is the photocurrent density (mA/cm<sup>2</sup>),  $j(E_{\text{rev}}^0 - |E_{\text{app}}|)$  is the total power output,  $j|E_{\text{app}}|$  is the electrical power input, and  $I_0$  is the power density of the incident light (mW/cm<sup>2</sup>).  $E_{\text{rev}}^0$  is the standard reversible potential (which is 1.23 V for the water-splitting reaction), and  $|E_{\text{app}}|$  is the absolute value of the applied potential  $E_{\text{app}}$ , which is obtained as

$$E_{\text{app}} = (E_{\text{meas}} - E_{\text{ocp}}) \quad (3)$$

where  $E_{\text{meas}}$  is the electrode potential of the working electrode at which  $j$  is measured under 100 mW/cm<sup>2</sup> visible light illumination, and  $E_{\text{ocp}}$  is the applied po-

tential at open circuit under the same illumination at which  $j$  is measured in the same electrolyte solution.  $E_{\text{meas}}$  and  $E_{\text{ocp}}$  are with respect to the same Ag/AgCl (saturated KCl) reference electrode.

Figure 7 shows that the photoconversion efficiency as a function of applied potential for the different photoanodes studied. According to Eq 2, a maximum photoconversion efficiency of 0.52% was obtained for the NTNA electrodes at an applied potential of 0.09 V versus Ag/AgCl (saturated KCl) electrode under 100 mW/cm<sup>2</sup> visible light illumination. However, under the same condition, a maximum photoconversion efficiency of 0.2% was observed for the TNA electrodes at an applied potential of 0.15 V, and a maximum photoconversion efficiency of 0.05% was achieved for the P25 nanoparticles at an applied potential of 0.17 V. The results clearly indicate that the NTNA electrodes could harvest visible light more effectively than the TNA electrodes and P25 nanoparticle electrodes under the same irradiation. The efficiency for NTNA in the visible compares favorably well with obviously reported efficiency of 0.27% for TiO<sub>2</sub> nanotubes doped with boron<sup>[4]</sup>.

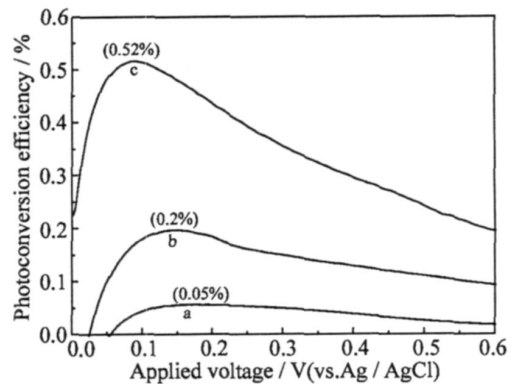


Fig 7 Photoconversion efficiency as a function of applied potential in 0.1 mol · L<sup>-1</sup> KNO<sub>3</sub> solution for P25 nanoparticle (a), TiO<sub>2</sub> nanowire (b) and N-doped TiO<sub>2</sub> nanowire (c) electrodes under visible light illumination

### 3 Conclusions

In summary, self-organized anodic anatase TiO<sub>2</sub> nanowire arrays doped with nitrogen have been successfully fabricated and systematically investigated



using a combination of FESEM, XRD, XPS, Mott-Schottky and photoelectrochemistry techniques. The structure of NTNA has been found to be in anatase phase. Nitrogen doping into the TiO<sub>2</sub> lattice results in a red-shift of absorption and enhanced photocurrent response in visible region relative to undoped TiO<sub>2</sub> films. Photocurrent measured with monochromatic incident light showed the IPCE (%) values of NTNA electrodes were obviously higher than that of commercial P25 nanoparticle electrodes. Furthermore, NTNA electrodes displayed a clear increase in its saturated photocurrent density under 100 mW/cm<sup>2</sup> visible light illumination than the undoped electrodes. A maximum photoconversion efficiency of 0.52% for NTNA electrodes was obtained, which was much higher than that on TNA and commercial P25 nanoparticle electrodes. The results suggest that N-doped TiO<sub>2</sub> nanowire arrays have good prospect for solar energy and other applications due to their improved optical and photoelectrochemical performances.

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## 氮掺杂 $\text{TiO}_2$ 纳米线阵列优越的可见光光电性能

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**摘要:** 成功制备了氮掺杂锐钛矿  $\text{TiO}_2$  纳米线, 并研究了它的光电化学性质. 结果表明, 与商用 P25  $\text{TiO}_2$  纳米粒子和未掺杂  $\text{TiO}_2$  纳米线相比, 氮掺杂  $\text{TiO}_2$  纳米线作为光阳极明显地提高了光电转换效率 (IPCE%), 在可见光区有明显光吸收; 在  $100 \text{ mW}/\text{cm}^2$  可见光光照下, 氮掺杂  $\text{TiO}_2$  纳米线具有最大的光电流密度和能量转换效率. 例如, 当电压为  $0.09 \text{ V}$  (vs  $\text{Ag}/\text{AgCl}$ ) 时最大能量转换效率为  $0.52\%$ , 均高于未掺杂  $\text{TiO}_2$  纳米线和商用 P25  $\text{TiO}_2$  纳米粒子的, 充分表现出它优越的光响应和光电化学性能, 在光电化学池、太阳能制氢等方面具有广泛的应用前景.

**关键词:** 氮掺杂;  $\text{TiO}_2$  纳米线阵列; 可见光吸收; 光电化学; 光催化