Computational and Experimental Study on Electronic Band Structure of Bismuth Ferrite: A Promising Visible Light Photocatalyst

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Abstracts

Electronic band structure of bismuth ferrite (BFO) is studied by computational and experimental methods. Bandgap of BFO is precisely determined using optical absorption spectra as well as density functional calculation (DFT). Both methods give a comparable result that BFO can have both of direct or indirect (very close to direct) bandgap of about 2.0~2.2 eV. Furthermore, electronic transition in BFO occurs via the unoccupied O 2p to the occupied Fe 3d states or the d–d transition in Fe 3d states. Intriguing electronic structure of BFO, a narrow bandgap and a multiple electronic transition route, render it as a promising candidate for a visible light photocatalyst.

Keywords: Bismuth ferrite, semiconductor, photocatalyst, water splitting

Introduction

Photoelectrochemical water platting is a one of promising way to produce sustainable energy without forming any greenhouse gases. [1] The solar energy can be directly converted to chemical energy such as hydrogen (H₂) by photocatalysis of water. Semiconductor metal oxides have
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have been widely studied as an active photoanode for photoelectrochemical water splitting due to their optimal band structure and electrochemical robustness in harsh electrolyte conditions. \[2\] Generally, a narrow bandgap with an appropriate band position is favorable for semiconductor metal oxides to effectively absorb visible light and split water.

Bismuth ferrite (BiFeO₃, BFO) has attracted a great attention from researchers owing to attractive electronic and magnetic properties. \[3, 4\] It was reported that BFO has a narrow direct bandgap of around 2.2 eV and is responsive to visible-light for photocatalytic water splitting. \[5\] However, several discrepancies were found in the literature regarding with the electronic band structure of BFO, especially between computational and experimental results. \[6, 7\] Difference values for the bandgap of BFO were reported. \[8\] Moreover, although the ferroelectric properties of BFO with the polarizable electronic configuration of Bi⁺ can enhance its photocatalytic activity, this gives difficulty to experimentally study a detailed electronic band structure of BFO. Thus, combined approach using computational as well as experimental methods is necessary to accurately investigate the electronic band structure of BFO.

In this work, we have prepared BFO via a facile sol–gel method and analyze its optical and electronic properties by measuring absorption spectra. Also, computational simulations were performed on the modeled BFO to precisely calculate electronic band structure of BFO. Our results reveal that BFO can have a direct or indirect (very close to direct) bandgap with a value of about 2.0 ~ 2.2 eV. Moreover, electronic transitions in BFO can be occurred via a two different routes either from the occupied O 2P to the unoccupied F 3d states or the d–d transition in Fe 3d states. Experimental and computational results for electronic structure of BFO were in good agreement each other. A narrow bandgap of BFO with a multiple electronic transition route highlights a potential use of BFO as an active visible light photocatalyst for water splitting.

Experimental Procedures

**Synthesis and characterization:** The BFO was synthesized using a facile sol–gel route. Typically, Bi(NO₃)₃·6H₂O and Fe(NO₃)₃·9H₂O in a stoichiometry ratio (1:2) were dissolved in ethylene glycol by continuous stirring at 80°C for 30 min. Then the reaction was carried out at 70°C for 10 h to get a gel. Then gel was heated in a muffle furnace at 400°C for 2 h followed by annealing at 550°C for 1 hr in a ramp rate 5°C/min. Finally the powder was collected by repeated washing with ethanol and water and dried at 60°C for overnight. Crystal structure of the BiFeO₃ were refined from powder X-ray diffractometer (Malvern Panalytical X’Pert³ Powder), We used Fullprof as a refinement tool for XRD patterns, Chi-square value as set to 2.75. In addition, these refined structures optimized by the wien2k 2D optimization code, The UV–vis spectrum of BFO powder was recorded using a JASCO UV Visible Spectrophotometer (V–670 PC).

**Computational methods:** First principles calculation of ferromagnetic R3c BiFeO3 executed using full potential linearized augmented plane wave (FP–LAPW) method, This density functional theory (DFT) ground state calculations performed...
The powder X-ray diffraction (XRD) pattern and crystal structure of as-synthesized pure BiFeO$_3$ (BFO) sample is shown in Fig. 1. The diffraction features of the sample (Fig. 1 (a)) shows hexagonal structure with R3c space group. All the peaks well indexed and matches with the single phase BFO according to standard crystallographic data and it consistent to the JCPDS card No. 71–2494.

The strong diffraction peaks of the sample (Fig. 1 (a)) suggest good crystalline nature. The 2θ position at 31.723° and 32.021° are found to be highest intensity represent (104) and (110) plane. To further understand the crystal structure and lattice parameters, Rietveld refinement of the powder XRD pattern for as-synthesized BFO (Fig. 1 (a)) was performed using FullPROF Software. A third–order polynomial was employed to integrate the background while the peaks were fitted using a pseudo–Voigt function. The half width of the diffraction peaks as a function of 2θ was estimated by the Caglioti equation. It is to be noted that the simulated XRD pattern (red line BFO$_{\text{calc}}$) is well matched with the experimental XRD peak (red dot BFO$_{\text{obs}}$) as shown in Fig. 1 (a). Moreover, the lattice parameters of 5.633 and 13.933 Å for a and c, respectively, were obtained from the refined structural parameters (Table 1). To demonstrate a successful refinement, the residuals (e.g., weighted profile residual (R$_{wp}$), profile residual (R$_p$), expected error residual (R$_e$) and structure factor (R$_f$)), associated with the goodness of fit (GOF = (R$_{wp}$/R$_e$)) and chi$^2$ ($\chi^2$), are also listed in Table 1. The low value of GOF and $\chi^2$ suggest
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The XRD pattern is well fitted to the hexagonal phase with R3C structure. Moreover, based on the refined parameters, the observed and calculated 2θ position along with the interplaner distance (d-values) is found to be little shifted, which may be ascribed to the difference in ionic radii. In addition, the crystal structure of as-synthesized BFO sample was visualized using the VESTA program (Fig. 1 (b)).

The electronic structure and bandgap of semiconductors is essentially linked with the optical absorption properties. The UV–VIS spectra of BFO for absorption from 400 to 700 nm at room temperature is shown in Fig. 2 (a). The sharp enhancement was observed in the UV–VIS spectra above the wavelength of 600 nm, suggesting a considerable absorption of visible light. This suggests a potential use of BFO as a visible–light active photocatalyst. Bandgap of BFO can be estimated from the relation between the absorption coefficient (α) and incident photon energy (hv) near the band edge following, 

\[ \alpha hν = A(hν-E_0)^n/2 \]

where \( h \) is Plank constant, \( ν \) is light frequency.

| Sample | Residuals | Lattice parameters | Volume (Å³) | 2θobs | 2θcalc | dobs | dcalc |
|--------|-----------|--------------------|-------------|-------|--------|-------|-------|
| BFO    | Rp        | a (Å) 5,633        | 382,853     | 22,403 | 22,400 | 3.9682| 3.9653|
|        | Rwp       | 17.8               |             | 27,372 | 27,298 | 3.8182| 3.8184|
|        | Rf        | 9.47               |             | 31,723 | 31,729 | 2.7911| 2.7911|
|        | Rm        | 0.718              |             | 32,041 | 32,044 | 2.3910| 2.3911|
|        | GOF       | 1.88               |             | 38,923 | 38,923 | 2.3112| 2.3112|
|        | Chi²      | 3.541              |             | 38,439 | 39,449 | 2.2844| 2.2829|

Fig. 2. (a) UV-vis diffuse reflectance absorption spectra of BFO and (b) analysis of UV–Vis measurement as a function of photon energy for (αhν)².
and $E_g$ is a bandgap, $\alpha$ can be calculated from the experimental UV–Vis spectra. Given that BFO has a direct bandgap, the value of 1 can be used for $n$. Then, the bandgap of BFO can be obtained by extrapolating the linear plot of $(\alpha h\nu)^2$ vs. incident photon energy ($h\nu$). As can be seen in Fig. 2 (b), the direct bandgap of BFO was calculated as about 2.04 eV which is comparable to the previously reported values. This reveals that BFO has a very narrow bandgap compared to other photocatalytic materials, highlighting its potential use for photoelectrochemical water splitting.

Computational calculations were employed to further study electronic band structure of BFO. Electronic band structure of BFO using DFT with GGA+U method is shown in Fig.3. Both of spin–up (Fig. 3 (a)) and spin–down (Fig. 3 (b)) states for Fe ion were considered for the calculations. The results indicate that BFO can have both of direct ($N$–$N$) and indirect ($\Gamma$–$N$, very close to direct with only 0.001 eV higher energy) bandgaps with values of 2.23 and 2.13 eV for spin–up and spin–down states, respectively. The predicted indirect bandgap of BFO, although very close to direct, is contradict with the experimental results. Notably, although an onset absorption starts below the bandgap in the absorption measurement (Fig. 2 (b)), this weak optical transition could be ignored for experimentally determining the bandgap. Thus, the absorption experimental data of BFO results in a direct bandgap for the most of case. Total density of states (t-DOS) of BFO where the Fermi level is set as 0 eV is presented in Fig. 4 (b). Notably, a weak ferromagnetic effect was clearly observed neat at the Fermi level as shown in the inset of Fig. 4 (a). Taking look into partial DOS (p-DOS) plots of BFO, Bi and O have a symmetric p-DOS for spin–up and spin–down states (Fig. 4 (b)), however Fe shows unsymmetrical p–DOS for the two different spin states. The valence band (VB) of BFO is consisted of Fe 3d, O 2p, and Bi 6p states. Additionally, the VB near at the Fermi level is mainly occupied by Fe 3d and O 2p states indicating that a strong hybridization is occurred between Fe and O atoms. In the conduction band (CB) of BFO, it was found that Fe 3d states predominantly occupy the CB in the range from 1 to 4 eV and Bi 6p states mainly occupy above 4 eV. Also, O 2p states are highly mixed with Fe 3d...
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and Bi 6p states in the CB. Hence, the bandgap of BFO is constructed with Fe 3d and O 2p states at the bottom of CB and the top of VB, respectively. In regard with the strong hybridization between Fe 3d and O 2p states in BFO, charge transfer can occur from the occupied O 2p to the unoccupied Fe 3d states or from VB to CB of the Fe 3d states through the d–d transition. These two different electronic transition routes in BFO can effectively facilitate charge transfer of electron–hole pairs possibly boosting its photocatalytic activity.

A simulated complex dielectric function of BFO is shown in Fig. 5. Note that \(\varepsilon_2\) (imaginary part of dielectric function) is essentially related with the electronic band structure where a peak in \(\varepsilon_2\) vs. energy plot corresponds to a multiple direct or indirect interband transition. The \(\varepsilon_2\) of BFO was started to increase approximately at 2.0 eV, where the first peak at 2.9 eV can be ascribed to the transitions from O 2p in VB to Fe 2d in CB or the d–d– transition in Fe 3d states. The peaks appeared at higher energy may be attributed to the transition from the occupied O 2p in VB to the unoccupied Fe 3d or Bi 6p states with a higher energy states in CB. Fig. 6 shows a simulation result on the absorption coefficient of BFO as a function of energy. It is found that the simulated absorption spectra of BFO gives a direct bandgap of 2.2 eV which is well consistent with our experimental results.

**Conclusion**

In summary, we have studied the electronic band structure of BFO, which was synthesized via a facile sol–gel method. Structural characterization was performed on the synthesized BFO powder by measuring the powder XRD pattern in combination
with the Rietveld refinement. Electronic band structure of BFO was studied by experimentally measuring absorption spectra and computationally simulating band structure. The experimental as well as computational results reveal that BFO can have both of direct or indirect (close to direct) bandgaps with a value of around 2.0 ~ 2.2 eV. Also, the simulated electronic structure of BFO indicated that a weak ferromagnetic effect is existed in BFO. According to the detailed study on DOS plots, electronic transition in BFO can occur via two different routes such as the O 2p to Fe 3d states or the d–d transition in Fe 3d states. The multiple electronic transition way in BFO with a narrow bandgap makes it as a promising photocatalytic material which can effectively absorb visible light.

Data accessibility

There are no additional data to accompany this manuscript. All relevant datasets are within the main body of the manuscript. All protocols and software used are stated fully in the methodology section. There are no coding lists for this research.

Author contributions

H.H. and A.K.N conceived the project; H.H. and A.K.N designed the experiments; H.H. and A.K.N wrote the manuscript; G.T., E.R.D., N.K.S, E.E. performed the detailed analysis on the data; G.T., E.R.D., N.K.S, S.J.K. performed the detailed analysis on structural data of the samples; All authors participated in analyzing the data and commented on the manuscript; All authors gave final approval for publication.

Competing interest

There are no competing interests for this manuscript.

Research ethics

No research which needs a local ethic approval is included in this work.

Animal ethics

No animal related experiments are included in this work.

Permission to carry out fieldwork

No field works are included in this work.

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