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Intense blue and green photoluminescence emissions at room temperature in barium zirconate powders

L.S. Cavalcante\textsuperscript{a,b,∗}, J.C. Szczancoski\textsuperscript{b}, J.W.M. Espinosa\textsuperscript{a,b}, V.R. Mastelaro\textsuperscript{c}, A. Michalowicz\textsuperscript{d}, P.S. Pizani\textsuperscript{b}, F.S. De Vicente\textsuperscript{c}, M.S. Li\textsuperscript{c}, J.A. Varela\textsuperscript{a}, E. Longo\textsuperscript{a}

\textsuperscript{a} Instituto de Química, UNESP, P.O. Box 355, 14801-907, SP, Araraquara, SP, Brazil
\textsuperscript{b} Departamento de Química e Física, UFSCar, P.O. Box 676, 13565-905, São Carlos, SP, Brazil
\textsuperscript{c} Instituto de Física de São Carlos, USP, P.O. Box 369, 13560-970, São Carlos, SP, Brazil
\textsuperscript{d} Université Paris XII, Faculté des Sciences et Technologie Bâtiment Marie Curie (F2)-345b, 94010, France

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\textbf{A B S T R A C T}

Intense blue and green photoluminescence (PL) emissions were observed at room temperature in barium zirconate (BaZrO\textsubscript{3}) powders prepared by chemical method. The powders were analyzed by X-ray diffraction (XRD), X-ray absorption near edge spectroscopy (XANES), extended X-ray absorption spectroscopy (EXAFS) and ultraviolet–visible (UV–vis) absorption spectroscopy. The XRD patterns indicated the presence of a secondary phase of BaCO\textsubscript{3} in BaZrO\textsubscript{3} powders heat treated at 773 K. K-edge XANES data revealed that Zr atoms present in at least two Zr environments. EXAFS analysis showed strong bond length dispersion in the first coordination shell around Zr atoms. Therefore, in this paper we report on the intense blue and green PL emission in BaZrO\textsubscript{3} powders that can be attributed to the two Zr environments or ZrO\textsubscript{5}–ZrO\textsubscript{6} clusters.

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1. Introduction

Recently, several studies have been dedicated to the photoluminescence phenomenon, especially in BaTiO\textsubscript{3} perovskite, mainly due to their excellent optical properties [1–3]. In particular, the literature reports several theories on the wide band visible emission observed in crystalline titanates, which belongs to a universal “green-luminescence”. This characteristic property is practically observed for all self-activated ABO\textsubscript{3} perovskites titanates [4]. The origin of green luminescence has been explained and discussed in many papers by different mechanisms, including self-trapped excitons [5], recombination of electron and hole polarons, charge transfer vibronic exciton [6], donor–acceptor recombination [7], transitions in MeO\textsubscript{5} complexes [8] and structurally disordered titanates [9–11]. However, few investigations on this phenomenon in zirconates have been reported [12–16]. In particular, the literature reports some works on luminescence of crystalline BaZrO\textsubscript{3} doped with europium [17–19]. In general, BaZrO\textsubscript{3} presents interesting properties for application in electroceramics and refractories owing to their thermal resistance and conductivity [20]. This perovskite can also be used as a protective agent against corrosion in the growth of superconductors [21,22]. Moreover, the excellent thermomechanical property [23] of this material is interesting for aerospace industries and correlated areas. This perovskite when doped can be used in fuel cells and proton conductors [24]. However, we have not knowledge about studies that explain the blue and green photoluminescence (PL) emissions in BaZrO\textsubscript{3} powders with intermediary structural order and/or structural order–disorder.

Therefore, in this paper we report on the intense blue and green PL emissions at room temperature in BaZrO\textsubscript{3} powders with structural order–disorder. The structural order–disorder in BaZrO\textsubscript{3} powders was analyzed by X-ray diffraction (XRD), X-ray absorption near edge spectroscopy (XANES) and extended X-ray absorption fine structure (EXAFS) spectroscopy techniques and ultraviolet–visible (UV–vis) absorption spectroscopy.

2. Experimental procedure

2.1. Synthesis of BaZrO\textsubscript{3} powders

BaZrO\textsubscript{3} powders were synthesized by the polymeric precursor method. Barium nitrate, Ba(NO\textsubscript{3})\textsubscript{2}·(99.9% Aldrich), zirconium n-propoxide, [Zr(OC\textsubscript{3}H\textsubscript{7})\textsubscript{4}] (99.9% Aldrich), ethylene glycol, C\textsubscript{2}H\textsubscript{4}O\textsubscript{2} (99.5% Synth) and citric acid, C\textsubscript{6}H\textsubscript{8}O\textsubscript{7} (99.5% Synth) were used as raw materials. Zirconium citrate was formed by the dissolution of Zr(OC\textsubscript{3}H\textsubscript{7})\textsubscript{4} in a citric acid aqueous solution under constant stirring. The citrate solution was stirred at 358 K until to obtain a clear and homogenous. Ba(NO\textsubscript{3})\textsubscript{2} was dissolved and added in a stoichiometric quantity to the Zr citrate solution. Ammonium nitrate, NH\textsubscript{4}NO\textsubscript{3}, dissolved and added in a stoichiometric quantity to the Zr citrate solution. Ammonium nitrate was added to the solution to increase the pH of the solution and to reduce the aggregation of the formed powders. After the addition of ammonium nitrate, the solution was stirred at 358 K until to obtain a clear and homogenous. The solution was then aged for several days at 358 K. After aging, the solution was filtered and washed with distilled water until to the pH of the solution was less than 7. The resulting precipitate was dried at 358 K and ground. The resulting powders were then calcined at 1273 K for 4 h. The calcined powders were then ground and sieved to obtain powders with particle sizes between 1 and 3 μm. The powders were then analyzed by X-ray diffraction (XRD), X-ray absorption near edge spectroscopy (XANES) and extended X-ray absorption spectroscopy (EXAFS) spectroscopy techniques and ultraviolet–visible (UV–vis) absorption spectroscopy.
2.2. Characterizations of BaZrO₃ powders

The crystalline phase was analyzed by X-ray diffraction (XRD) patterns recorded on a Rigaku-DMax2500PC with Cu Kα radiation in the 2θ range from 10° to 75° with a 0.02°/min. PL spectra in the range from 488 to 800 nm were taken with a U1000 Jobin-Yvon double monochromator coupled to a cooled GaAs photomultiplier and a conventional photon counting system. The 488.0 nm wavelength of an argon ion laser was used as excitation source, using a maximum output power kept at 30 mW. Cylindrical lens were used to prevent the sample from overheating. The slit width used was 100 μm. PL spectra in the range from 380 to 800 nm were measured with a Thermal Jarrel-ASH Monospec 27 monochromator and a Hamamatsu R446 photomultiplier. The 350.7 nm line of a krypton ion laser (Coherent Innova 90K) was used as excitation source, with the lasers nominal output power kept at 200 mW. X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) spectra of the BaZrO₃ powders were collected at the Zr K-edge using a Si (2 2 0) monochromator in the D04B-XAFS1 beam line. The powders were deposited on a polymeric membrane and the incident and transmitted X-ray beam were detected by ionization chambers filled with Ar gas. XANES spectra were measured from 50 eV below and 200 eV above the edge with energy step of 1.0 eV near the edge region. For comparison, all XANES spectra were background removed and normalized using as unity the 100 eV after the edge. The energy range of the Zr K-edge XANES spectra was 17,900–18,900 eV and it was calibrated using Zr foil. Data were collected at room temperature using energy steps of 2 eV and an integration time of 3 s. Three EXAFS spectra were collected for each sample and the average spectrum was used to perform the data analysis. The qualitative analysis of the EXAFS spectra was carried out by using the program set written by Michalowicz [27] according to the recommended procedures described in ref. [28]. Due to the low signal to noise ratio at high K values, the analysis of the EXAFS spectra were limited to the maximum value of 12 Å⁻¹. After atomic absorption removal and normalization, the k² (k) weighted EXAFS signal was Fourier transformed to R space in the 2.7–12.9 Å⁻¹ range. Each spectrum was Fourier transformed using a Kaiser apodisation window with τ = 2.5. The contribution of first coordination shell around zirconium atoms was extracted by a back Fourier transform in R distance space and then fitted using theoretical phase and amplitude functions as obtained from FEFF8.2 code [29]. Ultraviolet–visible (UV–vis) absorption spectra of optical absorbance on disordered and ordered BaZrO₃ powders were recorded using a Cary 5G spectrophotometer.

3. Results and discussion

3.1. X-ray diffraction analysis

The XRD patterns of BaZrO₃ powders heat treated at 773 and 973 K for 2 h in oxygen atmosphere are shown in Fig. 1. The presence of diffraction peaks can be used to evaluate the structural order or structural order–disorder of the material. BaZrO₃ phase was confirmed by comparison between the XRD patterns with the respective Joint Committee on Powder Diffraction Standards (JCPDS) card No. 06-0399. All diffraction peaks of BaZrO₃ powders heat treated at 973 K for 2 h were indexed as a cubic structure (see Fig. 1). However, BaZrO₃ powders heat treated at 773 K for 2 h showed diffraction peaks related to the BaZrO₃ cubic and also of barium carbonate (BaCO₃). Before complete structural organization, BaZrO₃ powders passes by an intermediary structural organization or structural order–disorder.

3.2. X-ray absorption near edge spectroscopy analysis

Fig. 2 shows the Zr K-edge XANES spectra of BaZrO₃ powders. The K-edge of Zr, the main absorption peak can be assigned to the 1s to 5p transitions [30]. As can be observed, XANES spectra of BaZrO₃ powders heat treated at 773 K present a significative difference in the main absorption edge in relation to the spectra of the BaZrO₃ powders were noted with a double peak (see Fig. 2).
tural order-disorder for the BaZrO₃ powder heat treated at 773 K for 2 h.

In sequence to quantify the structural differences observed on the XANES spectra, we analyze the EXAFS spectra of BaZrO₃ powders heat treated at 773 and 973 K. In this work, the XANES spectra are characteristic of Zr atoms at least in two Zr environments. Usually, EXAFS spectra provide information on the coordination chemistry of the probe atom, including such as average bond lengths and coordination numbers.

3.3. Extended X-ray absorption spectroscopy analysis

Fig. 3(a) shows the $k\chi(k)$ EXAFS spectra of BaZrO₃ powders heat treated at 773 K and Fig. 3(b) their respective $k^3\chi(k)$ Fourier transform magnitude.

EXAFS spectrum of crystalline powders is quite similar to that reported in the literature [35]. As can be seen in Fig. 3(a), EXAFS spectrum of BaZrO₃ powders heat treated at 773 K is highly smooth at high $k$ values, indicating that the structure is considerably disordered when compared to that the powders heat treated at 973 K. To obtain quantitative structural information on the Zr–O first coordination shell in both samples, the first peak of the Fourier transform magnitude presented in Fig. 3(b) was selected and again the Fourier transform was employed to obtain a filtered EXAFS spectrum related only to the first Zr–O coordination shell. The filtered EXAFS spectrum was then fitted using the theoretical phase and amplitude functions provided by the FEFF8.2 code [35].

![Fig. 3](image3.png)

Fig. 3. (a) $k$ weighted normalized EXAFS spectra of BaZrO₃ powders and (b) respective Fourier transform magnitude of the $k^3$-weighted EXAFS spectra.

![Fig. 4](image4.png)

Fig. 4. Comparison between filtered experimental EXAFS data (solid line) and refined data (dots) of BaZrO₃ powders heat treated at (a) 773 K and (b) 973 K for 2 h in oxygen atmosphere.

Fig. 4(a) and (b) show the experimental and best fit of the filtered EXAFS spectra of both samples. According to the fitting results presented in Table 1, the first coordination shell around Zr atoms in BaZrO₃ powders heat treated at 973 K is composed by 6 oxygen atoms situated at approximately 2.11 Å (see Fig. 4(b)).

These results are consistent with the XRD data of crystalline BaZrO₃ powders, $N_{Zr-O} = 6$, $R = 2.09$ Å [35]. On the other hand, in the case of BaZrO₃ powders heat treated at 773 K, which were characterized as being structurally ordered–disordered based on XRD data, the best fitting of the filtered EXAFS spectra was achieved with a structural model composed by 3 shells with a bond length in the range from 2.06 to 2.31 Å (see Table 1 and Fig. 4(a)). This strong bond length dispersion in the first coordination shell around Zr atoms for the BaZrO₃ powders heat treated at 773 K explains the significant difference observed in the intensity of the first peak of the Fourier transform localized between 1 and 2 Å (see Fig. 3(b)).

Table 1

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>$N$</th>
<th>$R$ (Å)</th>
<th>$\sigma^2$ (Å²)</th>
<th>$\Delta E$ (eV)</th>
<th>QF</th>
</tr>
</thead>
<tbody>
<tr>
<td>773</td>
<td>2.8 ± 0.3</td>
<td>2.18 ± 0.0008</td>
<td>0.000 ± 0.0002</td>
<td>2.3 ± 0.8°</td>
<td>1.47</td>
</tr>
<tr>
<td>973</td>
<td>5.8 ± 0.5</td>
<td>2.108 ± 0.0008</td>
<td>0.007 ± 0.002</td>
<td>2.0 ± 0.7</td>
<td>2.54</td>
</tr>
</tbody>
</table>

$N$ is the first coordination shell neighbor number, $\sigma$ is the Debye-Waller Factor, $R$ is the Zr–O mean bond length, $E$ is the threshold energy shift and QF is the quality factor [28].
3.4. BaZrO$_3$ structure and models

BaZrO$_3$ powders presented a cubic structure with a space group $Pm\bar{3}n$. The experimental lattice parameters values crystalline BaZrO$_3$ phase were $a = b = c = 4.186$ Å. These parameters were calculated using the least squares refinement of the UNITCELL-97 program [36]. The representation of an ordered BaZrO$_3$-o model was built through $1 \times 1 \times 2$ supercell (Fig. 5(a)) [37]. This ordered model can be designed as [ZrO$_6$]–[ZrO$_6$], since each Zr atom is surrounded by six O atoms. We assume that before complete crystallization of BaZrO$_3$ powders, i.e., before heat treatment temperature reach to 973 K, the structure of this material was composed by a mixture of ZrO$_6$ octahedra surrounded by Ba atoms. The ordered–disordered BaZrO$_3$-od model was formed by the displacement of one Zr atom in the [0 0 1] direction. This displacement was the simplest way to represent the two environments of Zr to show the [ZrO$_5$ · VO$_x$] complex clusters, where VO$_x$ and VO$_2$ are designed as square-base pyramid, and [ZrO$_6$] designed as octahedron. Therefore, BaZrO$_3$-od structure can be represented by [ZrO$_6$ · VO$_x$]–[ZrO$_6$], as shown in Fig. 5(b).

As can be seen in Fig. 5, this simple model suggests a mechanism for structural organization of BaZrO$_3$ powders prepared by the polymeric precursor method. After increase of heat treatment temperature occurs a reduction of oxygen vacancies in the BaZrO$_3$ lattice. This approach leads to a correlation between experimental data and model proposed. This slight order degree on structurally disordered materials was expected, since two or more atoms arranged near to each other on a stable configuration must necessarily have some order degree because of the existence of a minimum potential energy. Our purpose with the BaZrO$_3$-od model is to provide a simple scheme to help in the comprehension of PL emission mechanisms linked to the structural defects of the electronic structure without to suppress completely the geometry of the cell. Using the same distorted model, we have successfully explained the PL emission of several titanates [38–40] and zirconates titanates [41–43]. The model suggests that the increase of heat treatment temperature reduces the disorder in BaZrO$_3$ lattice, creating electron-captured oxygen vacancies. According to the equations using the Kröger-Vink notation by means of complex clusters [44a,b].

$$\text{[ZrO}_6\text{]}_x + \text{[ZrO}_5\cdot \text{VO}\_x\text{]} \rightarrow \text{[ZrO}_6\text{]}_x' + \text{[ZrO}_5\cdot \text{VO}^*\text{]}$$

(1)

$$\text{[ZrO}_6\text{]}_x + \text{[ZrO}_5\cdot \text{VO}^*\text{]} \rightarrow \text{[ZrO}_6\text{]}_x' + \text{[ZrO}_5\cdot \text{VO}^\ast\ast\text{]}$$

(2)

$$\text{[ZrO}_5\cdot \text{VO}^\ast\ast\text{]} + \frac{1}{2} \text{O}_2 \rightarrow \text{[ZrO}_6\text{]}$$

(3)

where [ZrO$_6$]$^x$ is a donor, [ZrO$_5$ · VO$^*$] is a donor–acceptor, and [ZrO$_5$ · VO$^\ast\ast$] is a acceptor.

3.5. Ultraviolet-visible absorption spectroscopy analysis

Fig. 6 shows UV-vis absorption spectra of BaZrO$_3$ powders heat treated at 773 and 973 K for 2 h in oxygen atmosphere.

The exponential optical absorption edge and optical band gap are controlled by the structural order–disorder degree in the BaZrO$_3$ lattice. The increase in the band gap can be associated to the reduction of defects in the lattice, which decrease the intermediary energy levels into the band gap region of disordered BaZrO$_3$ powders. The powders heat treated at 773 K presented a similar absorption behavior as in amorphous semiconductors, such as silicon and insulators (see Fig. 6(a)). Therefore, BaZrO$_3$ powders heat
Fig. 6. UV–vis absorbance spectra of BaZrO₃ powders heat treated at (a) 773 K and (b) 973 K for 2 h in oxygen atmosphere.

Fig. 7 illustrates the wide band model and PL spectra recorded at room temperature for the BaZrO₃ powders heat treated at 773 and 973 K for 2 h using two different excitation wavelengths: 350.7 and 488 nm.

Fig. 7(a) shows the lasers employed in the excitation of BaZrO₃ powders heat treated annealed at 773 and 973 K for 2 h. Depending upon the excitation wavelengths used is possible to promote electrons from the valence band to conduction band. The optical band gap for the BaZrO₃ powders heat treated at 773 K and 973 K were 4.82 eV and 4.86 eV, respectively. In this case, it was not verified an emission by band–band process, but due to the wide band process. Our wide band model presented in Fig. 7(b), before the absorption of $h\nu$, can occurs by two possible mechanisms: shallow holes (see Fig. 7(c), above) and deep holes (see Fig. 7(c), below). These mechanisms are responsible by different light emissions in disordered BaZrO₃ powders. This phenomena was not observed on structurally ordered powders, possibly due to the simultaneous treated at 973 K showed a typical band in the high energy region of the absorbance curve for ordered or crystalline materials (see Fig. 6(b)). In disordered BaZrO₃ powders, the absorbance measurements suggest a non-uniform on band gap structure with the presence of localized states. The optical band gap energy is related to the absorbance and photon energy, according to Wood and Tauc [45] as shown in Eq. (4):

$$h \nu \alpha \left( h \nu - E_{opt} \right)^{2},$$

where $\alpha$ is the absorbance, $h$ is the Planck constant, $\nu$ is the frequency, and $E_{opt}$ is the optical band gap.

In this case, optical band gap was determinate extrapolating the linear portion of the curve or tail. The obtained result for the BaZrO₃ heat treated at 773 K for 2 h was of 4.82 eV and 4.86 eV for BaZrO₃ crystalline. This observed behavior can be associated with the energy difference between the valence band and conduction band for this material.

3.6. Wide band model and photoluminescence analysis

Fig. 7 illustrates the wide band model and PL spectra recorded at room temperature for the BaZrO₃ powders heat treated at 773 and 973 K for 2 h using two different excitation wavelengths: 350.7 and 488 nm.

Fig. 7(a) shows the lasers employed in the excitation of BaZrO₃ powders heat treated annealed at 773 and 973 K for 2 h. Depending upon the excitation wavelengths used is possible to promote electrons from the valence band to conduction band. The optical band gap for the BaZrO₃ powders heat treated at 773 K and 973 K were 4.82 eV and 4.86 eV, respectively. In this case, it was not verified an emission by band–band process, but due to the wide band process. Our wide band model presented in Fig. 7(b), before the absorption of $h\nu$, can occurs by two possible mechanisms: shallow holes (see Fig. 7(c), above) and deep holes (see Fig. 7(c), below). These mechanisms are responsible by different light emissions in disordered BaZrO₃ powders. This phenomena was not observed on structurally ordered powders, possibly due to the simultaneous
4. Conclusions

The presence of $\text{[ZrO}_3\text{]}^\cdot$–$\text{[ZrO}_2\text{]}$ in the lattice. This behavior is agreement with XANES and EXAFS results and with the models described previously in this manuscript. Fig. 7(d) shows the excitation process due to the recombination between electrons ($e^-$) and holes ($h^+$) into band gap, which are responsible by the blue and/or green PL emission at room temperature.

The general aspect of the spectra is a broad band covering a large part of the visible spectra from 400 to 800 nm. A set of emission bands is distinctly recorded under the two wavelengths, with the peak position of each band shifts upward when the excitation wavelength increases. These two distinct energies (~3.54 and 2.54 eV) are able to excite different populations of electrons localized in additional levels in the forbidden band gap of disordered BaZrO$_3$ powders. The PL emission profile is typical of a multiphonon and multilevel process, i.e., a system in which relaxation occurs by several paths, involving the participation of numerous states into the band gap of the material. This behavior is related to the structural disorder of BaZrO$_3$ and confirms the presence of additional electronic levels in the forbidden band gap. Therefore, many of the oxygen vacancies are vacancy complexes on the intermediate structure. In this cubic structure, $\text{[ZrO}_5\text{]}^\cdot$ complex cluster is a donor candidate and $\text{[ZrO}_2\text{]}^\cdot$ an acceptor candidate. We speculated that these oxygen complex vacancies induce new energy levels in the band gap, which can be attributed to the zirconium–oxygen complex vacancy centers.

The blue emission can be attributed to shallow holes in the band gap of materials with a structural order–disorder. The green emissions are linked to deep holes into the band gap for more disordered materials. The PL emission can be attributed to the presence of the structural order–disorder degree in the lattice due to the presence of $\text{[ZrO}_2\text{]}^\cdot$ $\text{[V}_O\text{]}^\cdot$ and $\text{[ZrO}_2\text{]}^\cdot$ $\text{[V}_O\text{]}^\cdot$ complex clusters deeply inserted in the band gap. The increase of the structural order leads to a reduction of complex vacancies and consequently the PL emission disappears. The intensity of PL emission depends mainly on the interaction of these complex clusters and of the excitation wavelength. Time-resolved spectroscopy is necessary to confirm this statement, which has already been investigated by several papers [46–49].

4. Conclusions

BaZrO$_3$ powders prepared by a chemical method were characterized by XRD, XANES and EXAFS and UV–vis techniques. XANES and EXAFS investigations suggested that the defects in the BaZrO$_3$ lattice can be linked to the two environments Zr correlated with the $\text{[ZrO}_5\text{]}^\cdot$ $\text{[ZrO}_2\text{]}^\cdot$ complex clusters, indicating a possible oxygen deficiency in BaZrO$_3$ powders with structural ordered–disordered. The results also indicated that the structural evolution from order–disorder to order is due to the increase of heat treatment temperature, which promote a reduction of local disorder and favors the increase of band gap. BaZrO$_3$ powders obtained by the chemical method heat treat at 773 K presented an intense PL emission at room temperature around 541 nm when excited by 488 nm wavelengths and around 445 and 569 nm when excited by 350.7 nm wavelengths. Also it was observed that the use of wavelengths with energy close to the band gap value of the material are able to activate some energy levels into the band gap. We attributed the shallow holes with blue PL emission and the deep holes with a green PL emission in disordered BaZrO$_3$ powders.

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