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Abstract

We report the fabrication of colloidal hafnia nanoparticles (NPs) and nanoribbons (NRs) in deionized water achieved by femtosecond laser ablation. The average size of NPs and NRs varied in the range 13.5–18.0 nm and 10–20 nm, respectively, with varying input laser energy. At lower energies, the NPs were observed to be in pure monoclinic phase of HfO₂. However, at higher input energies, interestingly, both monoclinic and hexagonal phases corresponding to HfO₂ and Hf₆O were observed. Hf₆O is otherwise expected only at high pressures.

1 Introduction

Hafnium oxide (HfO₂) is one of the efficient high-*k* dielectric (~25) gate oxide materials that has replaced the SiO₂ in current integrated circuit technology [1, 2]. Additionally, HfO₂ also possesses superior optoelectronic properties such as high optical band gap (5.7 eV) and high refractive index (~2). The transparency of hafnia in the near-ultraviolet (near-UV) to far-infrared (far-IR) region encourages its usage in various applications such as astronomical Si-based CCDs [3], night vision and IR optical devices [4], UV-IR protective layers [5, 6], solar cell coatings [7], etc. In the current scenario, the technology is tending towards nanoscale to enhance and improve the properties of these materials for various applications.

 HfO_2 nanoparticles (NPs) have wide-ranging applications in various fields including bio-medical applications. Recent studies show that the inert behavior of HfO_2 NPs makes them suitable candidates for cancer therapy [8], nanocrystalline HfO_2 -based biosensors [9], HfO_2 nanowire-based

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ion-sensitive field effect transistor (ISFT) for pH sensors [10], X-ray contrast agent and mid-IR biosensor [11] applications. Recently, there have been reports where gamma and X-ray radiations were used to treat cancer with HfO₂ NPs, since these are better in absorbing high-energy radiation and in targeting cancer by localizing the radiation damage within the tumor tissues [12]. The main advantage of HfO_2 NPs is their cytotoxicity. Utilization of high atomic number (Z)nanoparticles creates ionization that releases electrons and subsequent free radicals traveling within a defined volume and generating energy deposition into this volume [8]. Here nanoparticles are critical to be able to enhance the therapeutic window, as they can disperse well in tissues and can interact with subcellular structures [8, 13, 14]. Needless to mention that the chemical reactivity is high for nanoparticles due to increased surface to volume ratio as compared to the bulk materials. This will further enhance the effectiveness of the material for cancer treatment. However, the quantum size effects pertaining to the electrical and optical properties are not that significant in this case as the size of the HfO_x NPs is bigger than the corresponding Bohr exciton radii.

The material scientists and physicists have adopted several synthesis methods to fabricate the HfO_2 NPs. The cubic HfO_2 NPs were prepared by microwave-assisted reduction and oxidation methods [15]. Monoclinic hafnia NPs were prepared by annealing the ALD-grown hafnia thin films [16]. HfO_2 nanorods were prepared by injection method [17]. Radio frequency (RF) magnetron sputtering method [18], chemical route method [19], and nanosecond (ns) laser ablation techniques have also been employed [20, 21]. Picosecond (ps) laser ablation methods have recently been



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employed successfully to deposit thin films of superior quality [22, 23]. Particularly, short pulse laser ablation method is one of the versatile techniques to synthesize the materials in the nanoscale region in a liquid environment. Using laser ablation with femtosecond (fs) pulses, one can change the material from bulk form to nanomaterial by evaporation, sublimation and condensation processes. Further, one can tune the material's properties such as particle size, phase and shape by varying the pulse energy, wavelength and repetition rate. In the literature, several reports demonstrate the efficacy of synthesizing NPs by fs laser ablation method [24–33]. To the best of our knowledge, there are no reports on the fabrication of HfO₂ NPs using fs laser ablation though there are few reports on NPs obtained using ns laser ablation. In an earlier report, HfO₂ NPs were prepared by ns laser ablation of pure Hf target in different liquid environments and the obtained NPs size varied from 4.3 to 5.3 nm in different liquid environments [21]. They observed that the produced hafnia NPs were in the monoclinic low temperature phase and in the tetragonal and fcc high-temperature phases. Herein, we report on the fabrication of HfO₂ NPs, nanoribbons (NRs) using fs ablation from bulk HfO₂ in deionized water (DIW). The NPs were characterized using grazing incident X-ray diffraction (GIXRD), high-resolution transmission electron microscope (HRTEM), selective area electron diffraction (SAED) and micro-Raman techniques.

2 Experimental details

HfO₂ pellets were prepared using 99.9% pure commercial HfO₂ powder with a grain size of 20–30 μ m. The powder was compressed into 5 mm thick and 1 cm diameter pellets under a pressure of 20 MPa and sintered at 500 °C for three hours. At this condition, the phase of the pellet was purely monoclinic. These monoclinic HfO2 pellets were submerged in deionized water containing Pyrex cell. The effective height of liquid layer above HfO₂ pellet was maintained at 5 mm during the ablation process. The ablation was performed using a Ti:sapphire laser (LIBRA, Coherent, USA) delivering 800 nm pulses with a duration of ~ 50 fs and at a repetition rate of 1 kHz. The beam waist on the target surface was ~ 50 μ m, which was estimated by considering line structure width from scanning electron microscope (SEM) images according to the method proposed by Barcikowski et al. [34]. The NPs are fabricated by irradiating the target surface with multiple laser pulses. During the ablation, the sample was translated with the help of motorized stages with velocities of 0.25 mm/s. The number of pulses per spot was calculated using a method presented in our earlier studies [35] and it was 200. The pulse to pulse spatial separation was 0.25 µm (in this case).

The target was placed normal to the laser beam on a twodimensional motorized stage (nanodirect). The computer program has been developed in such a way that the stage can move X-Y with a velocity of 250 µm/s [36]. The sample was scanned over $5 \times 5 \text{ mm}^2$ and each line was separated by 100 µm. The same procedure was carried out for different laser energies of 200, 300, 400 and 500 µJ. The colloidal HfO₂ NPs were collected in airtight glass bottles. The colloidal NPs were drop-casted on carbon-coated Cu TEM grids and silicon substrates and subjected to subsequent wetting at 70 °C for 1 h to remove the moisture. HRTEM and SAED measurements were performed on TEM grids to examine the size distribution and phase evaluation of the generated NPs. Micro-Raman spectroscopy measurements were performed using a Horiba Raman spectrometer at an excitation wavelength of 632 nm. GIXRD measurements were performed using Bruker D8 Discover diffractometer equipped with Cu $K\alpha$ ($\lambda = 1.5405$ Å) X-ray source to investigate the particle size and change in phase. Grazing incident angle was 5° and that scan range was set between 20° and 80°.

3 Results and discussion

3.1 HRTEM and SAED measurements

Figure 1a-d illustrate the TEM images of laser-ablated HfO₂ which contain both NPs and NRs. As seen from the histograms shown in Fig. 1a-d right-hand side, a wide distribution of size (5-100 nm) was observed for all the input energies. The average NP size varied from 13.5 to 18.8 nm with increasing laser energies (200–500 μ J). Based on our literature knowledge and experience, we firmly believe that both peak energy and fluence will affect the observed NPs' sizes, shapes and phases. It has also been demonstrated that picosecond ablation is superior to femtosecond ablation in terms of NPs' yield. Furthermore, we did not find any reports from the literature that described the relation between size and yield of NPs with pulse energy and scan speeds in a single study. Further detailed studies are planned in this direction in the future. The right-hand bottom side of Fig. 1a-d depicts the high-resolution TEM images clearly indicating that the NPs are extended to form NRs. It is also observed that the density of NRs increases with increase in laser energy, which was found to be amorphous. Similar observations of nanochain formation in various materials ablated in a water environment have been reported elsewhere [37, 38]. The probable reason for the observed nanochain formation could be due to collision-induced aggregation and laser-induced sintering [39]. A few other studies of occurrence of nanochains in water environment are attributed to the quenching of plasma plume generated during the laser ablation process [40]. The growth mechanism of nanochains/

Fig. 1 TEM images of HfO₂ NPs synthesized in DIW at different laser energies a 200 μ J, b 300 μ J, c 400 μ J and d 500 μ J. Right side of each image depicts the corresponding size distribution histograms and below are the high-resolution TEM images illustrating the NRs. (*d*) represents the average nanoparticle diameter, while ' σ ' represents the deviation



nanoribbons may not be due to the vapor–liquid–solid [41, 42] process, in which catalytic-assisted mechanism plays a vital role in the formation of nanochains/nanoribbons. Normally, the metal NPs act as catalyst active sites, but in the present case no metal was used. The growth of nanochains could be due to a vapor–solid process [43], in which vapor was produced from the HfO₂ target due to the high-temperature plasma generated at the target liquid surface and got deposited as nanoclusters through the aggregation near to the target surface. As the ablation progresses, continuously emitting plasma generates more HfO_x vapor and results in the formation of more nanoclusters, which are favorable sites for adhesion of additional HfO_x molecules and consequently results in the formation of NRs [44]. Femtosecond laser ablation can modify the material locally to attain very high temperatures/pressures at very early time scales (first few picoseconds) and that can lead to the micro-explosions within the ablated area [45–47]. However, the exact mechanism of NRs formation is still unclear and needs further systematic studies.

The phase of the HfO_x nanostructures is comprehended using HRTEM and SAED data, which is presented in Fig. 2a–d. Figure 2a illustrates the SAED pattern of HfO_x NPs which confirms the monoclinic phase with 'd' spacings of 0.28 nm and 0.31 nm, corresponding to the planes of (111) and (-111) at lower laser energies. Figure 2b, c illustrate the SAED patterns clearly suggesting the existence of rhombohedral and hexagonal phases in samples ablated at higher laser energies. Figure 2d depicts the HRTEM image and the 'd' spacing of 0.48 nm and 0.44 nm corresponding



Fig. 2 a-c The electron diffraction patterns of monoclinic, rhombohedral, hexagonal structures, respectively. d HRTEM images of HfO₂ NPs. The inset of d shows IFFT pattern

to the planes of (100) and (101), respectively, of hexagonal Hf₆O (or) HfO₂ phase. Furthermore, the EDS data also confirmed the Hf/O ratio of 45.6/54.4 at lower energy and 78.5/21.4 at higher energy. We have also observed that at lower input energies the NPs exhibited monoclinic polycrystalline nature, while for higher input energies, pure crystalline nature with a combination of monoclinic and hexagonal structures is seen. Therefore, we believe that the fs laser ablation of HfO₂ pellets in deionized water leads to the formation of HfO₂ NPs when ablated at lower input energies, whereas Hf (metal)-rich (like Hf₆O) NPs are formed at higher energies in otherwise same conditions. We believe that this is an important result that provides useful information to understand the basic process of ultrafast laser ablation of oxide materials in liquids. The metallic nature of NPs generated at higher input energies needs to be thoroughly investigated. The advantage with the present technique is that the produced NPs are bare and possess ligand-free surfaces, which are desirable and beneficial in high-k dielectric applications.

3.2 GIXRD measurements

HfO₂ exhibits distinct phases depending on the synthesis conditions; some are pressure-induced phase transitions [48], while others are temperature-induced phase transitions [49]. All these phase transitions are dependent on Hf and O concentration levels as well. GIXRD measurements have been performed on HfO, NPs drop-casted on Si substrates, and GIXRD patterns are shown in Fig. 3. For lower energies of 200 µJ and 300 µJ, the NPs exhibited a monoclinic phase. Further increase in the energy to 400 µJ and 500 µJ has resulted in the combination of monoclinic and hexagonal phase for the generated NPs. GIXRD patterns strongly support the observations from HRTEM and SAED data which demonstrated distinct phases of HfO, at different laser fluences. The 2θ values at 28.3° and 31.5° confirm the monoclinic phase of the corresponding (-111) and (111)planes of HfO₂. These peaks match well with JCPDS file #01-006-0318 (monoclinic HfO₂). The 2θ values of 35.2° and 44.2° confirm the presence of hexagonal phase, which is noticed for higher energies. These peaks again match well with JCPDS file #01-078-5817 (hexagonal Hf₆O). The GIXRD data coordinated well with the hexagonal Hf₆O ratios. TEM and EDS (energy dispersive spectroscopy) data confirmed that the hafnium-rich oxide nanostructures are formed by laser ablation at higher energies. Several theoretical studies [50-52] have predicted the occurrence of Hf_6O and other binary hafnium oxides (e.g., Hf_8O_7) at very high pressures, which can possibly be present during highenergy ablation using fs pulses. Formation of this new and high-pressure stable phase (Hf₆O) is of fundamental interest in view of the complexity of laser matter interactions at



Fig. 3 GIXRD patterns of HfO_2 NPs prepared at different laser energies and drop-casted on Si substrates (*m* monoclinic, *h* hexagonal structures)

extreme conditions. Here, it is important to note that these h.c.p-based metal (Hf)-rich binary oxides have been identified as potential candidates for cladding materials in nuclear reactors. Moreover, these oxygen-deficient HfO_x alloys are naturally stable in an oxygen atmosphere even at high temperatures [50, 53–55]. These superior qualities qualify them as suitable candidates for hard coatings in several applications. Further detailed studies are essential to confirm the formation of these unusual and exotic structures.

3.3 Micro-Raman studies

Hafnium oxide exhibits a total of about 36 vibrational modes. However, among those, 18 modes (9 A_{o} + 9 B_{o}) are Raman active, 15 modes $(8 A_u + 7 B_u)$ are IR active and the remaining 3 modes are acoustic vibrations [56]. Monoclinic phase of HfO₂ exhibits all the 18 vibration modes and tetragonal phase exhibits 3 IR and 3 Raman modes [57]. Micro-Raman spectra of the HfO₂ NPs drop-casted on Si substrates are shown in Fig. 4. The Raman peaks observed at 300 and 521 cm⁻¹ represent the characteristic lines of Si and the corresponding FWHM is $\sim 3.4 \text{ cm}^{-1}$. Bulk HfO₂ Raman peak at 523 cm⁻¹ matched exactly with the monoclinic phase of HfO₂ [58–60]. We have observed a deviation of $2-4 \text{ cm}^{-1}$ for each peak in HfO_x NPs with respect to those of pure HfO₂. Monoclinic HfO₂ NPs exhibited a peak at 523 cm⁻¹ that is beneath the dominant Si 521 cm⁻¹ peak. The experimental and theoretical calculations of HfO2 vibrational modes for monoclinic, tetragonal, orthorhombic and cubic phases have been reported in literature [61-64]. However, in the present work, we have not observed any tetragonal, cubic



Fig. 4 Raman spectra of HfO_2 NPs prepared at different laser energies and drop-casted on Si substrates. All the major peaks observed are indexed along with the silicon peak near 521 cm⁻¹

or orthorhombic phases. For the input energies of 300 µJ and 400 µJ, the Raman peak positions matched with the original peaks, but the intensity ratios were different. For the case of 500 µJ input energy, the two dominant peaks at 136 and 152 cm^{-1} merge into a single peak at 144 cm^{-1} . Similarly, the peaks at 244 and 258 cm⁻¹ merge and produce a dominant peak at 250 cm⁻¹. Most of the observed lower vibrational modes correspond to metal (Hf), while the higher range modes are oxygen-dominated modes. According to the existing reports [64], the higher order modes concur with the original results, while lower modes merge and yield a dominant peak as a function of Hf content and laser ablation energy. We conclude that the fs ablation of HfO₂ pellets in DIW leads to the formation of monoclinic HfO₂ NPs when ablated at lower input energies, whereas Hf (metal)-rich (like Hf_6O) NPs are formed at higher energies. We believe this is an important result providing useful information towards understanding the basic processes involved in ultrafast laser ablation of oxide materials in liquids. The metallic nature of NPs generated at higher input energies needs to be thoroughly investigated.

4 Conclusions

In summary, HfO_2 NPs are fabricated in liquids using fs laser ablation technique with varying input pulse energies. The size of the HfO_2 NPs increases from 13.5 to 18 nm with increase in laser energy from 200 to 500 µJ. Along with NPs, 10–20 nm wide and few 100 nm long NRs have also been observed. The density of these NRs increases with increasing input laser energy. At lower input energy, HfO_2 NPs exhibited monoclinic structure and at higher energy, both monoclinic and hexagonal structures were observed. The variation in phase change was confirmed from the SAED, GIXRD and Raman spectral data, including the formation of a new phase (Hf_6O) which is otherwise formed at high pressures.

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References

- 1. W.J. Zhu, T.-P. Ma, IEEE Electron Device Lett. 23, 97–99 (2002)
- L.A. Lipkin, J. Palmour, IEEE Trans. Electron Devices 46, 525 (1999)
- 3. M. Lesser, Opt. Eng. 26, 911-915 (1987)
- M. Fadel, O.A. Azim, O.A. Omer, R.R. Basily, Appl. Phys. A 66, 335–343 (1998)
- A. Callegari, E. Cartier, M. Gribelyuk, J.F. Okorn-Schmidt, T. Zabel, J. Appl. Phys. 90, 6466–6475 (2001)
- M. Toledano-Luque, E. San Andrés, A. del Prado, I. Mártil, M.L. Lucía, G. González-Díaz, F.L. Martínez, W. Bohne, J. Röhrich, E. Strub, J. Appl. Phys. **102**, 044106 (2007)
- X.-Y. Zhang, C.-H. Hsu, Y.-S. Cho, S.-Y. Lien, W.-Z. Zhu, S.-Y. Chen, W. Huang, L.-G. Xie, L.-D. Chen, X.-Y Zou, S.-X. Huang, Appl. Sci. 7, 1244 (2017)
- L. Maggiorella, G. Barouch, C. Devaux, A. Pottier, E. Deutsch, J. Bourhis, E. Borghi, L. Levy, Future Oncol. 8(9), 1167–1181 (2012)
- 9. J. Shim, J. Rivera, R. Bashir, Nanoscale 21, 10887–10893 (2013)
- M. Lee, A. Baraket, N. Zine, M. Zabala, F. Campabadal, A. Errachid, N. Jaffrezic-Renault, Sens. Transducers 27, 233–238 (2014)
- T.L. Mc Ginnity, O. Dominguez, T.E. Curtis, P.D. Nallathamby, A.J. Hoffman, R.K. Roeder, Nanoscale 8, 13627–13637 (2016)
- 12. L. Allison et al., Future Oncol **10**, 2329–2344 (2014)
- J. Marill, N.M. Anesary, P. Zhang, S. Vivet, E. Borghi, L. Levy, A. Pottier, Radiat. Oncol. 9, 150 (2014)
- J. Galon, M. Lae, J. Tharaiat, S. Carrere, Z. Papai et al., J. Clin. Oncol. 36(15), e15149–e15149 (2018)
- N. Kumar, B.P.A. George, H. Abrahamse, V. Parashar, S.S. Ray, J.C. Ngila, Sci. Rep. 7, 9351 (2017)
- W. Zhou, S.V. Ushakov, T. Wang, J.G. Ekerdt, A.A. Demkov, A. Navrotsky, J. Appl. Phys. **107**, 123514 (2010)
- K.K. Bharathi, N.R. Kalidindi, C.V. Ramana, J. Appl. Phys. 108, 083529 (2010)
- M. Dhanunjaya, S.A. Khan, A.P. Pathak, D.K. Avasthi, S.V.S. Nageswara Rao, J. Phys. D Appl. Phys. 50, 505301 (2017)
- X. Liu, Y. Chen, L. Wang, D.L. Peng, J. Appl. Phys. 113, 076102 (2013)
- M.A. Pugachevskii, V.I. Panfilov, J. Appl. Spectrosc. 81, 640–643 (2014)
- N.G. Semaltianos, J.M. Friedt, R. Chassagnon, V. Moutarlier, V. Blondeau-Patissier, G. Combe, M. Assoul, G. Monteil, J. Appl. Phys. **119**, 204903 (2016)
- E.G. Gamaly, A.V. Rode, B. Luther-Davies, J. Appl. Phys. 85, 4213 (1999)
- E.G. Gamaly, A.V. Rode, B. Luther-Davies, J. Appl. Phys. 85, 4222 (1999)

- V.S. Vendamani, S. Hamad, V. Saikiran, A.P. Pathak, S. Venugopal Rao, V.V. Ravi, K. Kumar, S.V.S. Nageswara Rao, J. Mater. Sci. 50, 1666–1672 (2015)
- G.K. Podagatlapalli, S. Hamad, S. Venugopal Rao, J. Phys. Chem. C 119, 16972–16983 (2015)
- 26. S. Hamad, G. Krishna Podagatlapalli, M.A. Mohiddon, S. Venugopal Rao, Appl. Phys. Lett. **104**, 263104 (2014)
- 27. D. Zhang, B. Gökce, S. Barcikowski, Chem. Rev. **117**, 3990–4103 (2017)
- J. Xiao, P. Liu, C.X. Wang, G.W. Yang, Prog. Mater Sci. 87, 140–220 (2017)
- H. Zeng, X.-W. Du, S.C. Singh, S.A. Kulinich, S. Yang, J. He, W. Cai, Adv. Funct. Mater. 22, 1333–1353 (2012)
- D. Zhang, J. Liu, P. Li, Z. Tian, C. Liang, Chem. Nano Mater. 3, 512–533 (2007)
- E.G. Gamaly, A.V. Rode, B. Luther-Davies, V.T. Tikhonchuk, Phys. Plasmas 9, 949–957 (2002)
- 32. E.G. Gamaly, A.V. Rode, Appl. Phys. A 278, 1-11 (2018)
- C. Hnatovsky, V. Shvedov, W. Krolikowski, A. Rode, Phys. Rev. Lett. 106, 123901 (2011)
- S. Barcikowski, A. Menéndez-Manjón, B. Chichkov, M. Brikas, G. Račiukaitis, Appl. Phys. Lett. 91, 083113 (2007)
- G. Krishna Podagatlapalli, S. Hamad, S.P. Surya, S. Sreedhar, M.D. Prasad, S. Venugopal Rao, J. Appl. Phys. 13, 073106 (2013)
- S. Venugopal Rao, G.K. Podagatlapalli, S. Hamad, J. Nanosci. Nanotechnol. 14, 1364–1388 (2014)
- 37. T.X. Phuoc, J. Mater. Sci. Nanotechnol. 2, 1-7 (2014)
- V.S. Vendamani, A. Tripathi, A.P. Pathak, S. Venugopal Rao, A. Tiwari, Mater. Lett. 192, 29–32 (2017)
- 39. H. He, W. Cai, Y. Lin, B. Chen, Chem. Commun. **46**, 7223–7225 (2010)
- O.V. Overschelde, J. Dervaux, L. Yonge, D. Thiry, R. Snyders, Laser Phys. 23, 055901 (2013)
- 41. R.S. Wagner, W.C. Ellis, Appl. Phys. Lett. 4, 89-90 (1964)
- Z.R. Dai, J.L. Gole, J.D. Stout, Z.L. Wang, J. Phys. Chem. B 106, 1274–1279 (2002)
- 43. E. Rudy, P. Stecher, J. Less Common Met. 5, 78-89 (1963)
- 44. D. Shin, R. Arroyave, Z.K. Liu, Calphad 30, 375–386 (2006)
- 45. J. Wallenius, D. Westlen, Ann. Nucl. Energy 35, 60-67 (2008)
- J.Q. Hu, Y. Bando, Q.L. Liu, D. Golberg, Adv. Funct. Mater. 13, 493–496 (2003)

- S. Juodkazis, A. Vailionis, E.G. Gamaly, L. Rapp, V. Mizeikis, A.V. Rode, MRS Adv. 1, 1149–1155 (2016)
- S. Juodkazis, K. Nishimura, S. Tanaka, H. Misawa, E.E. Gamaly, B. Luther-Davies, L. Hallo, P. Nicolai, V. Tikhonchuk, Phys. Rev. Lett. 96, 166101 (2006)
- R. Buividas, G. Gervinskas, A. Tadich, B.C.C. Cowie, V. Mizeikis, A. Vailionis, D. de Ligny, E.G. Gamaly, A.V. Rode, S. Juodkazis, Adv. Eng. Matt. 16, 767–773 (2014)
- Y. Al-Khatatbeh, K.K.M. Lee, B. Kiefer, Phys. Rev. B 82, 144106 (2010)
- J. Zhang, A.R. Oganov, X. Li, H. Dong, Q. Zeng, Phys. Chem. Chem. Phys. 14, 17301–17310 (2015)
- J. Zhang, A.R. Oganov, X. Li, K.-H. Xue, Z. Wang, H. Dong, Phys. Rev. B 92, 184104 (2015)
- 53. P. Blaise, B. Traore (2015), http://arxiv.org/abs/1511.07665v1
- L. Bayarjargal, W. Morgenroth, N. Schrodt, B. Winkler, V. Milman, C.R. Stanek, B.P. Uberuaga, High Press. Res. 37, 147–158 (2017)
- N. Selvakumar, H.C. Barshilia, K.S. Rajam, Sol. Energy Mater. Sol. Cells 94, 1412–1420 (2010)
- 56. X. Zhao, D. Vanderbilt, Phys. Rev. B 65, 233106 (2002)
- M. Yashima, H. Takahashi, K. Ohtake, T. Hirose, M. Kakihana, H. Arashi, Y. Ikuma, Y. Suzuki, M. Yoshimura, J. Phys. Chem. Solids 57, 289–295 (1996)
- P.E. Quintard, P. Barberis, A.P. Mirgorodsky, T. Merle-Mejean, J. Am. Ceram. Soc. 85, 1745–1749 (2002)
- A. Jayaraman, S.Y. Wang, S.K. Sharma, L.C. Ming, Phys. Rev. B 48, 9205–9211 (1993)
- J.S. Quintero-García, B.A. Puente-Urbina, L.A. García-Cerda, O.S. Rodríguez-Fernández, E. Mendoza-Mendoza, Mater. Lett. 159, 520–524 (2015)
- S.N. Tkachev, M.H. Manghnani, A. Niilisk, J. Aarik, H. Mandar, J. Mater. Sci. 40, 4293–4298 (2005)
- V. Jayaraman, G. Bhavesh, S. Chinnathambi, S. Ganesan, P. Aruna, Mater. Express 4, 375–383 (2014)
- B. Zhou, H. Shi, X.D. Zhang, Q. Su, Z.Y. Jiang, J. Phys. D Appl. Phys. 47, 115502 (2014)
- C.W. Li, M.M. Mc Kerns, B. Fultz, Phys. Rev. B 80, 054304 (2009)