Dielectric property of (001) one-axis oriented CaBi$_4$Ti$_4$O$_{15}$-based thin films and their temperature dependence

Yohta KONDOH,* Shota OGAWA,†,** Junichi KIMURA,** Takanori KIGUCHI,**
Toyohiko J. KONNO,*** Hiroshi FUNAKUBO*** and Hiroshi UCHIDA,*†

*Department of Materials and Life Sciences, Sophia University, Tokyo 102-8554, Japan
†Department of Innovative and Engineered Materials, Tokyo Institute of Technology, Yokohama 226-8503, Japan
**Institute for Material Research, Tohoku University, Sendai 980-8577, Japan

We proposed a thin-film capacitor with a stable temperature coefficient of capacitance (TCC) based on bismuth layer-structured dielectrics, CaBi$_4$Ti$_4$O$_{15}$. Two types of doping were conducted to lower the dielectric loss in a higher temperature range above 300°C, i.e., Mn ion to compensate for lattice defects in crystalline grains and Bi$_{12}$SiO$_{20}$ to form a grain boundary phase were attempted in order to improve the insulating property of the oriented CaBi$_4$Ti$_4$O$_{15}$ films. (001) one-axis oriented Mn-doped or Bi$_{12}$SiO$_{20}$-doped CaBi$_4$Ti$_4$O$_{15}$ films (with Mn or Bi$_{12}$SiO$_{20}$ content up to 3.0 or 1.75%) were fabricated successfully on (111)Pt/TiO$_2$/[100]Si substrates buffered by (001)Ca$_2$Nb$_3$O$_{10}$ nanosheets. These films exhibited a relatively lower loss factor in the temperature range from R.T. up to 400°C. In particular, the behavior of TCC on the Bi$_{12}$SiO$_{20}$-doped CaBi$_4$Ti$_4$O$_{15}$ film was significantly stable, with a change in capacitance, $\Delta C/C_{R.T.}$, within ±10% even at 400°C.

©2014 The Ceramic Society of Japan. All rights reserved.

Key-words: Dielectrics, Thin film, Calcium bismuth titanate, Chemical solution deposition (CSD), Doping, Temperature coefficient of capacitance (TCC)

1. Introduction

Recently, dielectric capacitors with a stable temperature coefficient of capacitance, TCC, have been strongly required for high-temperature electronics applications with SiC- or GaN-based semiconductors in order to design integrated-circuits specialized for driving under high-temperature environments, such as direct-mount control circuits for automobile engines, motors, electric lighting, etc.\(^1\)\(^-\)\(^3\) Although these applications need stable TCC behavior with a lower absolute TCC value, TCC, while in a wide temperature range together with moderate dielectric permittivity, almost all present capacitor have hardly satisfied these requirements; for example, typical ceramic capacitors, which consist of BaTiO$_3$-based materials, exhibit drastic dielectric degradation around 150°C due to their Curie-type phase transition.\(^4\),\(^5\) Therefore, we have explored novel concepts of material applications in order to construct high-temperature dielectric capacitors.

The authors have reported unique dielectric capacitors with a low TCC behavior less than 10% up to 400°C, which consisted of epitaxial or one-axis oriented bismuth layer-structured dielectrics (BLSDs) with a chemical composition of MBi$_4$Ti$_4$O$_{15}$ (M = Ca and Sr, etc.).\(^6\),\(^7\),\(^8\) The capacitors are based mainly on the strong anisotropy of their dielectric and insulating properties, which is significantly dependent on their crystal orientation, i.e., a large difference in spontaneous polarization, coercive voltage, dielectric permittivity, and its temperature dependence on BLSD single crystal along to the a-(b-) to up their Curie temperature, $T_C$, above 400°C.\(^9\),\(^10\)\)\) Our pioneering research on epitaxial (001)BLSD films on (100)SrRuO$_3$/[(100)SrTiO$_3$] accomplished stable TCC values of approximately less than ±200 ppm/K (from R.T. up to 400°C),\(^6\),\(^7\),\(^8\) which is significantly lower than those reported for conventional (Ba$_{0.7}$Sr$_{0.3}$)TiO$_3$ films, approximately ±800 ppm/K (from R.T. up to 200°C),\(^4\),\(^5\),\(^8\) and also as a lowered leakage current density and moderate $\varepsilon_r$. These properties have significantly attractive performance for high-temperature electronic applications superior to the conventional dielectric capacitors.

However, in the subsequent research on one-axis-oriented (001)BLSD films, which aimed for material synthesis on ubiquitous substrates, i.e., templated silicon wafers, a degraded TCC behavior of approximately ±800 ppm/K (from R.T. up to 400°C) had only been confirmed despite the films’ out-of-plane crystal orientation being similar to that of epitaxial (001)BLSD films.\(^12\),\(^13\),\(^14\) In particular, the stability of the TCC behavior had been degraded in the temperature range above 300°C due to the increment of dielectric loss, whereas it was comparable from room temperature up to 300°C. The authors assume that the dielectric loss in the high-temperature region would be caused by enhanced current conduction through the dielectric layer, resulting in the degradation of TCC behavior. In the case of thin-film capacitors that consist of one-axis oriented dielectric films, the leakage current generally can arise through two conduction paths (Fig. 1): intragranular current conduction owing to lattice defects and intergranular current conduction along grain boundaries. Particularly, the second conduction path would be a unique route only for the one-axis oriented films and hardly seen for the epitaxial films, which resulted in the enhanced current conduction degrading the TCC behavior.

In the present paper, the authors propose two strategies for improving the TCC behavior of one-axis oriented (001)BLSD films: suppressing the intragranular current conduction by doping manganese (Mn) ion and suppressing the grain-boundary current conduction by introducing bismuth silicate (Bi$_{12}$SiO$_{20}$, BSO) as...
the grain boundary phase. Mn ion doping is a standard technique for improving the insulating properties of various perovskite and layered-perovskite dielectrics by charge compensation of oxygen vacancies in crystalline grains.\(^{15-19}\) Also, grain-boundary modification has been widely used for controlling the current conduction of polycrystalline ceramic materials.\(^{20}\) The authors expect that both approaches will contribute to suppressing the dielectric loss, especially in a high-temperature range above 300°C, and then improve the TCC behavior of one-axis oriented BLSD films consequently.

2. Experimental

All thin films for the dielectric capacitors were fabricated by using a CSD technique. The precursor solutions for CaBi\(_4\)Ti\(_4\)O\(_{15}\) (CBTi) films with a chemical composition of Ca:Bi:Ti = 1.00:4.20:4.00 (in molar ratio) were prepared by dissolving Ca(NO\(_3\))\(_2\)·4H\(_2\)O, Bi(NO\(_3\))\(_3\)·5H\(_2\)O and Ti(OCH\(_2\)CH\(_2\)CH\(_3\))\(_4\) in 2-methoxyethanol solvent with concentrated nitric acid and acetylacetone. The precursor solutions for Mn- and BSO-doped CBTi films were prepared by using (CH\(_3\))\(_2\)COOH\(_2\)Mn-4H\(_2\)O, (CH\(_3\))\(_2\)COOH\(_2\)Bi and Si(OCH\(_2\)CH\(_2\)CH\(_3\))\(_4\) with the reagents describe above. The nominal compositions were CaBi\(_4\)Ti\(_{4-x}\)Mn\(_x\)O\(_{15}\) (x = 0–10.0%) and CaBi\(_4\)Ti\(_{4-x}\)Mn\(_x\)O\(_{15}\) + yBi\(_2\)SiO\(_{20}\) (y = 0–1.75%). The concentration of the solutions was approximately 0.02 mol/dm\(^3\). The solution was spin-coated on substrates at a rate of 3000 rpm for 50 s, followed by a drying process at 150°C for 3 min and a pyrolysis process at 400°C for 3 min with a hot plate. The crystallization was accomplished by RTA heat-treatment at 750°C for 3 min after each drying/pyrolysis process. The coating was repeated 18 times in total to obtain the resulting films with thicknesses of approximately 300 nm.\(^{15,25}\) Platinized silicon wafers buffered by nanosheet calcium niobate Ca\(_2\)Nb\(_2\)O\(_{10}\) templates (001)ns-CN/(111)Pt/TiO\(_2\)/(100)Si were prepared in order to fabricate BLSD films with preferential crystal orientation. The ns-CN templates were supported on (111)Pt/TiO\(_2\)/(100)Si by dip coating with an aqueous nanosheet dispersion prepared via ion exchange and chemical exfoliation of layered metal oxide KCa\(_2\)Nb\(_2\)O\(_{10}\).\(^ {24,25}\)

The constituent phase and crystal orientation of the films were identified by X-ray diffraction (XRD) with a Rigaku RINT2000 diffractometer. The microstructure and film thickness of the films were observed by scanning electron microscopy (SEM) with a Hitachi S4500 electron microscope. The surface morphology of the samples was observed by atomic force microscopy (AFM) with a Veeco Innova scanning probe microscope. The dielectric property was evaluated by using an Agilent technology 4294A impedance analyzer, after the deposition of Pt top electrodes at 200μm φ by electron-beam deposition. The measurement was performed under an oscillation field of 3.3 kV/cm (voltage: 0.1 V) and frequency of 10\(^{-2}\)–10\(^{3}\)Hz. Also, the leakage current of the resulting film was measured by using an Agilent technology 4155B semiconductor parameter analyzer, under a DC voltage applied with 0.1 V/step up to 10 V.

3. Results and discussion

3.1 Suppression of intragranular current conduction by doping Mn ion

Mn-doped CBTi films were fabricated on (001)ns-CN/(111)Pt/TiO\(_2\)/(100)Si substrates. Figure 2 shows XRD patterns (2θ-ω scan) of the Mn-doped CBTi films with various Mn contents, CaBi\(_4\)Ti\(_4\)Mn\(_x\)O\(_{15}\) (x = 0–10.0%). All of the films exhibited diffraction peaks of a single phase of BLSD (m = 4) without a secondary phase, except for Pt and Si from substrates. Preferential (001) BLSD peaks were observed for the resulting films with an Mn content of x = 0–3.0%, whereas there was an intensive (119) peak only for the film with x = 10.0%, meaning random crystal orientation. There was no significant peak shift with the Mn content; Out-of-plane lattice parameters, c-axes, of the CBTi and Mn-doped CBTi films (x = 0–10.0%) were ranged between 4.067 and 4.078 nm. These results indicated that the one-axis oriented (001) BLSD films were successfully grown on the (001)ns-CN layer with pseudo-perovskite crystal lattice, as discussed previously.\(^ {19}\) for Mn-doped CBTi films with lower Mn contents (x = 0–3.0%) but were hardly grown for the film with higher Mn content (x = 10.0%) to yield random oriented BLSD film. This could be due to the segregation of an excessive Mn component from the BLSD crystal that generates a trace amount of secondary phase (not found on XRD) and then prevents the preferential crystal growth (001) BLSD, not due to the lattice mismatch between Mn-doped CBTi and ns-CN because there was no significant lattice strain caused by the Mn doping. Surface AFM images of the Mn-doped CBTi films with various Mn contents (x = 0, 3.0 and 10.0%) are shown in Fig. 3. These images exhibited that the films mainly consisted of
isotropic crystal grains with sizes of several hundred nanometers. The Mn-doped CBTi films included relatively uniform crystal grains independent of the Mn amount, whereas a small amount of larger crystal grains was dispersed in pure CBTi films without Mn doping. Mn doping could prevent inhomogeneous grain growth in the CBTi film. No significant difference in the surface roughness RMS was observed.

The dielectric property of the Mn-doped CBTi films was evaluated in a wide temperature range from ambient up to 400°C. First, Fig. 4 shows the relative dielectric constant ($\varepsilon_r$) and loss factor (tan $\delta$) as a function of frequency for the Mn-doped CBTi films with various Mn contents. The $\varepsilon_r$ values for the films with an Mn content of $x = 0$–3.0% were almost constant around 200 in the frequency range of $10^2$–$10^6$ Hz, while the film with $x = 10.0\%$ exhibited a lower $\varepsilon_r$ value of approximately 150. There was no drastic lowering in the $\varepsilon_r$ value related to the dielectric relaxation. The tan $\delta$ values for all films were below 0.1 in the frequency range of $10^2$–$10^6$ Hz. The $\varepsilon_r$ values of approximately 200 for the Mn-doped CBTi films with $x = 0$–3.0% were almost the same as those values for epitaxial (001) BLSD films fabricated on (100),SrRuO$_3$/[(100)SrTiO$_3$]$_{0.95}$ However, it decreased slightly with Mn doping up to $x = 10.0\%$, which is due to the formation of a trace secondary phase as mentioned before.

The temperature dependences of capacitance ($\Delta C/C_{R,T}$) and tan $\delta$ are plotted in Fig. 5. Here, $\Delta C = C_{\text{Temp.}} - C_{R,T}$, $C_{\text{Temp.}}$ is the capacitance at the sample temperature at the measurement, and $C_{R,T}$ is that at room temperature. The $\Delta C/C_{R,T}$ values for the Mn-doped CBTi films were almost stable within ±10% up to 200°C. However, they increased with the temperature drastically in the temperature range above 300°C, except for with $x = 3.0\%$, which decreased gradually up to 300°C and then increased slightly at 400°C. A drastic increment of the tan $\delta$ value was observed for the pure CBTi ($x = 0$) and heavily doped CBTi films ($x = 10.0\%$) in the temperature range above 200°C, while it was relatively suppressed for the Mn-doped CBTi films with $x = 0.1$–3.0%. The changes in $\Delta C/C_{R,T}$ and tan $\delta$ observed in Fig. 5 were reversible against the sample heating/cooling process. These results suggested that the Mn doping with moderate amount ($x = 0.1$–3.0%) contributed to suppressing the dielectric loss, especially in a higher temperature range (more than 200°C), as well as stable TCC behavior a little.

Also, the temperature dependence of leakage current conduction for the Mn-doped CBTi film was evaluated, because authors assumed that current conduction can cause the degradation of TCC behavior, especially at higher temperature range, as described on the section of introduction (Fig. 1). Figure 6 shows the typical current density ($J$)–applied bias ($E$) curves for the
Mn-doped CBTi film ($x = 3.0\%$) measured at various temperatures from R.T. up to 400°C. The current density under a lower applied field ($< 50\text{kV/cm}$) increased drastically at 300°C and above, whereas it kept the order of $10^6\text{A/cm}^2$ below 300°C. This tendency means that the current conduction through the dielectric capacitor was still enhanced above 300°C even for the Mn-doped CBTi film with $x = 3.0\%$, although improved $TCC$ behavior was confirmed in Fig. 5. The breakdown voltage of the Mn-CBTi film was specifically lower only at R.T., which was reversible behavior against sample the heating/cooling process. This might be due to the effect of moisture adsorption,

This might be due to the effect of moisture adsorption,

$$29, 30)$$

reversible behavior against sample the heating/cooling process.

$$3.2 \text{ Suppression of grain-boundary current conduction by introducing Bi}_{12}\text{SiO}_{20} \text{ as grain boundary phase}$$

Subsequently, BSO-doped CBTi films were fabricated on (001)ns-CN/(111)Pt/TiO$_2$/(100)Si substrates. Figure 7 shows XRD patterns (20-0 scan) of the BSO-doped CBTi films with various BSO contents, Ca$_{10}$Bi$_{4}$Ti$_4$O$_{15}$ + yBi$_{12}$SiO$_{20}$ ($y = 0–1.75\%$).

All of the films exhibited diffraction peaks of (001) BLSD planes, indicating the preferential crystal growth of (001) BLSD normal to the substrate surface buffered by the (001)ns-CN layer successfully, as similar to the case on the Mn-doped CBTi films. The authors recognized that there was no solid solution related to BSO doping because there was no significant peak shift with the BSO addition for all samples. It is also supported by other experimental results that a small amount of BSO phase appeared for the BSO-doped CBTi films with higher BSO contents ($y = 1.00–1.75\%$). No significant degradation in the crystallinity caused by BSO doping was confirmed for all samples as well as the decrease in the crystal orientation, which is somehow different from the case for Mn doping.

Surface AFM images of the BSO-doped CBTi films with various BSO contents ($x = 0.50$, 1.00 and 1.75%) are shown in Fig. 8. As similar to the Mn-doped CBTi films in Fig. 3, the BSO-doped CBTi films also consisted of relatively uniform and isotropic grains of several hundred nanometers independent of the BSO content. Also, there was no significant difference in the surface roughness related to the BSO doping. These images did not show any evidence for the phase segregation of BSO as grain boundary phase as expected at the beginning of the present research, owing to a small amount added BSO that can be negligible in AFM observation.

Figure 9 shows dielectric properties, i.e., $\varepsilon_r$ and $\tan\delta$ as a function of frequency, for the BSO-doped CBTi films with various BSO contents. The $\varepsilon_r$ values for all films were almost constant around 200 in the frequency range of $10^2–10^6\text{Hz}$ independent of the BSO content. No significant dielectric relaxation was confirmed for these data. The $\tan\delta$ values for all films were below 0.05 in the frequency range of $10^2–10^6\text{Hz}$. These results indicated that the BSO-doped CBTi films up to $y = 1.75$ possessed a room-temperature dielectric property comparable with the epitaxial (001) BLSD films as well as one-axis-oriented Mn-doped CBTi films, as confirmed in Fig. 4. Furthermore, the authors note that the loss factors for the BSO-doped CBTi films were relatively lower than those for the Mn-doped CBTi films, which suggests that the dielectric loss on CBTi capacitors could be suppressed by the BSO doping regardless of its significantly low BSO content.

Figure 10 shows the temperature dependences of $\Delta C/C_{R.T}$ and $\tan\delta$ for the BSO-doped CBTi films with various BSO contents. Note that the $\Delta C/C_{R.T}$ values for the films with higher BSO contents ($y = 1.00$ and 1.75%) were stable within ±10%
Unfortunately, the authors could hardly increase furthermore drastically at 300°C and above.

Changes in capacitance ($\Delta C/C_{R,T}$) and $\tan \delta$ as function of measurement temperature for BSO-doped CBTi films on (001)ms-CN/(111)Pt/TiO$_2$/Si substrate, with $y = 0$–1.75% in CaBi$_4$Ti$_4$O$_{15} + y$Bi$_2$SiO$_{30}$ (during heating).

Even up to 400°C, whereas those for lower BSO contents ($y = 0$ and 0.50%) increased with the temperature to exceed +20% at 400°C, as similar to the Mn-doped CBTi films in Fig. 5. We also note that the temperature dependences of $\tan \delta$ for the BSO-doped CBTi films kept stable values within 5% in a wide temperature range between R.T. and 400°C, while a drastic increment of $\tan \delta$ was found at a higher temperature range for pure or Mn-doped CBTi films. These changes were reversible against the sample heating/cooling process. These results suggested that BSO doping suppresses the dielectric loss on the CBTi capacitor as assumed before and then prevents apparent charge input in a higher temperature range that results in stable TCC behavior. The effect of BSO doping on the TCC behavior of CBTi films looks significantly larger than that of Mn doping.

Typical current density ($I$)—applied bias ($E$) curves for the BSO-doped CBTi film ($x = 1.0%$) measured at various temperatures from R.T. up to 400°C, shown in Fig. 11, were made in order to evaluate the temperature dependence of the leakage current conduction. The current densities at R.T. and 100°C (approximately the order of $10^{-7}$ A/cm$^2$) were significantly lower than for pure CBTi$^{21,23}$ and Mn-doped CBTi films. The densities increased gradually up to $\sim 10^{-6}$ A/cm$^2$ at 200°C and then increased furthermore drastically at 300°C and above. Unfortunately, the authors could hardly find any reasonable relationship between the leakage current density and the loss factor ($\tan \delta$ in Fig. 10) for these data, although we at first expected that somehow there would be a synchronized change in accordance with dielectric loss based on current conduction. BSO doping might work more effectively under a higher frequency (AC) bias rather than under a DC bias.

4. Conclusion

Two dopants, Mn and BSO, were introduced in one-axis oriented CBTi films in order to improve their TCC behavior in high-temperature regions. The preferential crystalline growth of (001)BLSD was maintained even after Mn- or BSO-doping up to $x = 3.0$% or $y = 1.75$% without significant morphological change. The room-temperature dielectric constant for these samples was approximately 200, which is comparable to epitaxial (001)CBTi films grown by MOCVD. Mn doping suppressed the $\tan \delta$ value slightly in a higher temperature range above 300°C, although these samples still exhibited a drastic increment in TCC value in a higher temperature range. The BSO-doped CBTi films exhibited significantly stable TCC behavior even up to 400°C, within ±10%, as well as a lowered $\tan \delta$ of less than 5%. The TCC values of the Mn-doped CBTi film ($x = 3.0$%) and BSO-doped CBTi film ($y = 1.00$%) were approximately +169 and +205 ppm (from R.T. up to 400°C), respectively, although the doping hardly suppressed the DC leakage current conduction in a higher temperature range.

We concluded that a small amount of dopants, used for modifying intra- or intergranular structures, contributed to suppressing the dielectric loss on BLSD films successfully in a wide temperature range. These concepts would be of help for constructing thin-film capacitors aimed for high-temperature electronics applications.

Acknowledgements This research was supported by the New Energy and Industrial Technology Development Organization (NEDO) and the Center for Integrated Nanotechnology Center at Tohoku University and also by the Nanotechnology Network Project of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of the Japanese Government.

References

1) H.-S. Chin, K.-Y. Cheong and A. R. Ismail, Metall. Mater. Trans., B, Process Metall. Mater. Proc. Sci., 41B, 824–832 (2010).
2) C. Buttay, D. Planson, B. Allard, D. Bergogne, P. Bevilacqua, C. Joubert, M. Lazar, C. Martin, H. Morel, D. Tournier and C. Raynaud, Mater. Sci. Eng., B, 176, 283–288 (2011).
3) R. S. Pengelly, S. M. Wood, J. W. Milligan, S. T. Sheppard and W. L. Pribble, IEEE Trans. Microw. Theory Tech., 60, 1746–1783 (2012).
4) P. Padmini, T. R. Taylor, M. J. Lefevre, A. S. Nagra, R. A. York and J. S. Speck, Appl. Phys. Lett., 75, 3186–3188 (1999).
5) C. B. Parker, J. P. Maria and A. I. Kingon, Appl. Phys. Lett., 81, 340–342 (2002).
6) K. Takahashi, M. Suzuki, T. Kojima, T. Watanabe, Y. Sakashita, K. Kato, O. Sakata, K. Sumitani and H. Funakubo, Appl. Phys. Lett., 89, 029901 (2006).
7) K. Takahashi, M. Suzuki, T. Oikawa, T. Kojima, T. Watanabe and H. Funakubo, Chem. Vap. Depos., 12, 136–142 (2006).
8) J. Kimura, I. Takuwa, M. Matsushima, S. Yasui, T. Yamada and H. Funakubo, J. Appl. Phys. Lett., 114, 027002 (2013).
9) Y. Park, M. Miyayama and T. Kudo, J. Ceram. Soc. Japan, 107, 413–418 (1999).
10) H. Irie and M. Miyayama, Appl. Phys. Lett., 79, 251–253 (2001).
11) H. Irie, M. Miyayama and T. Kudo, J. Appl. Phys., 90, 4089–4094 (2001).
12) Y. Mizutani, H. Uchida, H. Funakubo and S. Koda, Jpn. J. Appl. Phys., 48, 09KA10 (2009).
13) Y. Mizutani, T. Kiguchi, T. J. Konno, H. Funakubo and H. Uchida, Jpn. J. Appl. Phys., 49, 09MA02 (2010).
14) Y. Kondoh, K. Sasajima, M. Hayashi, J. Kimura, I. Takuwa, Y. Ebara, H. Funakubo and H. Uchida, Jpn. J. Appl. Phys., 50, 09NA04 (2011).
15) J.-Y. Kim, C.-R. Song and H.-I. Yoo, J. Electroceram., 1, 27–39 (1997).
16) C. Voisard, D. Damijanovic and N. Setter, J. Eur. Ceram. Soc., 19, 1251–1254 (1999).
17) S. K. Singh and H. Ishiwara, Solid State Commun., 140, 430–434 (2006).
18) Y. Noguchi, K. Yamanoto, Y. Kitanaka and M. Miyayama, J. Eur. Ceram. Soc., 27, 4081–4084 (2007).
19) Y. Nomura, Y. Hiruma, H. Nagata and T. Takenaka, Jpn. J. Appl. Phys., 49, 09MD02 (2010).
20) R. Wasser and M. Klee, Integr. Ferroelectr., 2, 1–4 (1992).
21) W. Huehner, S. C. Zhang, B. Gilmore, M. L. Krogh, B. C. Schultz, R. C. Pate, L. F. Rinehart and J. M. Lundstrom, Dig. Tech. Paper: IEEE Pul. Pow. Conf., 2, 1242–1245 (1999).
22) M. Touzin, D. Goeuriot, C. Guerret-Pécourt, D. Juvé and H.-J. Fitting, J. Eur. Ceram. Soc., 30, 805–817 (2010).
23) S. Ogawa, Y. Kondoh, J. Kimura, H. Funakubo and H. Uchida, Jpn. J. Appl. Phys., 51, 09LA16 (2012).
24) H. Uchida, K. Sakurai, I. Okada, H. Matsuda, T. Iijima, T. Kojima, T. Watanabe and H. Funakubo, Jpn. J. Appl. Phys., 42, 5990–5993 (2003).
25) Y. Ebina, T. Sasaki and M. Watanabe, Solid State Ionics, 151, 177–182 (2002).
26) F. F. Xu, Y. Ebina, Y. Bando and T. Sasaki, J. Phys. Chem. B, 107, 9638–9645 (2003).
27) K. Kikuta, K. Noda, S. Okumura, T. Yamaguchi and S. Hirano, J. Sol-Gel Sci. Technol., 42, 381–387 (2007).
28) T. Shibata, K. Fukuda, Y. Ebina, T. Kogure and T. Sasaki, Adv. Mater., 20, 231–235 (2008).
29) S. Agarwal, G. L. Sharma and R. Manchanda, Solid State Commun., 119, 681–686 (2001).
30) J. D. Baniecki, J. S. Cross, M. Tsukada and J. Watanabe, Appl. Phys. Lett., 81, 3837–3839 (2002).