Structure and electrical properties of Ba$_3$TaGa$_3$Si$_2$O$_{14}$ single crystals grown by Czochralski method

Haruki USUI$^1$, Hiraku KUSAKABE$^1$, Makoto TOKUDA$^2$, Kazumasa SUGIYAMA$^2$, Takuya HOSHINA$^1$, Takaaki TSURUMI$^1$ and Hiroaki TAKEDA$^{1,3}$

$^1$School of Materials and Chemical Technology, Tokyo Institute of Technology, Meguro, Tokyo 152–8552, Japan
$^2$Institute for Materials Research (IMR), Tohoku University, Sendai 980–8577, Japan
$^3$Graduate School of Science and Engineering, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama 338–8570, Japan

Ba$_3$TaGa$_3$Si$_2$O$_{14}$ (BTGS) bulk single crystals were grown by the Czochralski method. The crystal structure of BTGS has been refined using single-crystal X-ray diffraction data with a precision corresponding to an $R$ index of 0.018. The crystal structure is isostructural to La$_3$Ga$_5$SiO$_{14}$ which has the trigonal space group $P\bar{3}21$ and $Z = 1$, and the distribution of each cation is ordered in each site. Material constants and resistivity of the crystal were measured up to 550 °C. The results indicate that the BTGS crystal is a good candidate for piezoelectric applications in elevated temperatures.

©2020 The Ceramic Society of Japan. All rights reserved.

Key-words : Langasite, Crystal growth, Crystal structure, Piezoelectricity, High temperature

1. Introduction

In the last two decades, piezoelectric single crystals with higher temperatures were high in demand for gas sensors, gas injectors, accelerometers, combustion pressure sensors, etc. The currently promising candidates are as follows: La$_3$Ga$_5$SiO$_{14}$ (langasite; LGS) family crystals,$^{1-4}$ rare-earth calcium oxoborate ReCa$_4$(BO$_3$)$_3$ ($Re =$ rare earth elements, ReCOB) crystals,$^{5,6}$ gallium phosphate GaPO$_4$,$^7,8$ gehlenite Ca$_2$Al$_2$SiO$_7$ and related crystals$^9-12$ AIN, and its modified crystal$^{13}$ or thick films.$^{14-16}$ Among them, langasite-type single crystals are attractive piezoelectric materials, because the crystals show no phase transitions up to their melting temperature and can be easily grown in large sizes using the Czochralski (Cz) method.$^{17,18}$ Recently, combustion pressure sensors made of the LGS and La$_3$Ta$_5$Ga$_5$Si$_{14}$ (LTG) substrates have been developed in high scale in a laboratory.

The langasite-type crystals belong to the trigonal crystal system, point group 32, and space group $P\bar{3}21$. In the crystal structure, there are four kinds of cation sites and the chemical formula is represented as $A_3BC_3D_2O_{14}$. The crystal structure is schematically shown in Fig. 1. The $A$ and $B$ represent a decahedral site and an octahedral site, respectively. $C$ and $D$ represent tetrahedral sites, with the $D$ site being smaller than the $C$ site. Langasite-type crystals are classified into two types depending on their site occupation patterns.$^{19}$ One is known as a crystal with the disordered structure (such as LGS, LTG, Ca$_3$Ga$_2$Ge$_4$O$_{14}$,$^{20}$ Na$_2$CaGe$_2$O$_{14}$,$^{21,22}$), in which at least one of the four cation sites is occupied by two and more different elements, e.g. the $D$ site is occupied by both Ga and Si in the LGS crystal. The other is called a crystal with the ordered structure such as Sr$_3$TaGa$_3$Si$_2$O$_{14}$ (STGS), in which all cation sites are occupied by a single type of element.$^{22}$ In Refs. 23, 24, ionic size preferences of cation site in the langasite-type crystals are reported as follows:

---

Fig. 1. A schematic of the langasite-type crystal structure viewed along [001] direction.

©2020 The Ceramic Society of Japan

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by-nd/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
A = Na⁺, Sr²⁺, La³⁺ (ca. 1.22 Å)
B = Ga³⁺, Sn⁴⁺, Nb⁵⁺, Ta⁵⁺ (ca. 0.65 Å)
C = Ga³⁺, Ge⁴⁺ (ca. 0.43 Å)
D = Si⁴⁺, Ge⁴⁺, Al³⁺ (ca. 0.33 Å)

Based on the above data, STG with the ordered structure was synthesized. Moreover, it has been reported²⁵ that an increase in lattice parameter a leads to an increase in the piezoelectric constants |d₁₁| of the langasite-type crystals. Hence, for the further development of new compounds, Ba₃Ta₂Ga₂Si₉O₁₄ (BTGS) crystals were also synthesized by the Cz method.²⁵-²⁷ Surface acoustic wave filters performed in the BTGS crystals indicate superior properties compared to those of LGS. However, to the knowledge of the authors, details of the crystal structure of BTGS and its piezoelectric properties at high temperatures have not been reported.

In this study, we describe the crystal structure and the electroacoustic constants of BTGS single crystals prepared successfully by the Cz method. We also report the temperature dependence of piezoelectric d₁₁ constant and electrical resistivity ρ.

2. Experimental procedures

The growth process of BTGS single crystals was described in detail in our previous reports.²⁵,²⁶ The BTGS crystals were grown by a conventional RF-heating Cz method using a platinum crucible (50 mm in diameter and height). Powders of 99.99% purity BaCO₃, Ta₂O₅, Ga₂O₃, and SiO₂ were used as the starting materials in stoichiometric composition. The powders were mixed and calcined at 1300 °C for 30 h in the air. The phases of the as-calcined powders were identified by powder X-ray diffraction. The pellet was charged in a Pt crucible (50 mm in diameter and height). The growth atmosphere was the air. The pulling rate and the rotation rate were 0.5–1.0 mm/h and 20–25 rpm, respectively. The important knowledge to avoid overheating of the raw materials after melting. The overheating lead the crystalline form of BTGS to become amorphous phase before growth process. The density of the grown crystals was measured by the Archimedes method using distilled water at 23 °C.

Single crystals cut from the grown boule were ground to a sphere and used for the structure analysis. Diffraction intensities were collected at room temperature using a Rigaku automated four-circle diffractometer. Detailed information on the data collection and refinement are summarized in Table 1. Intensities were corrected for Lorentz, polarization, and absorption factors using the Rigaku program. The crystal structure was refined using the full-matrix least-squares program SHELXL97.²⁸

BTGS belongs to the tetragonal point group 32. The material constants consist of two dielectrics, two piezoelectric, and six elastic compliance constants (εᵢᵢ, dᵢᵢ, and sᵢᵢ, respectively). As described in Refs. 29, 30, the material constants were determined using an impedance/gain phase analyzer (Agilent HP 4194A). We measured the mechanical series resonance frequency fᵣ and parallel resonance frequency fₑ of equivalent resonators and then evaluated the electromechanical coupling factor kᵢᵢ and piezoelectric constants. The equivalent resonators were fabricated in the forms of plates and rotating cuts according to vibration modes such as the face-shear, thickness-shear, and length-extensional modes.²⁹ The dielectric constant εᵢᵢ was determined by measuring the capacitances of the resonators while considering parasitic capacitance. The temperature dependences of these constants were also measured in the temperature range from room temperature to 550 °C at every 50 °C step. The changes in d₁₁ and the resistivity ρ in the temperature range from room temperature to 550 °C were investigated. The gold and silver-palladium electrodes were used for measurement at a high temperature.

3. Results and discussion

BTGS crystal boules with a 20 mm diameter and 50–80 mm length were obtained by the Cz method. The crystals had smooth surfaces and were transparent and colorless. Many bubbles were observed in the center parts of all the crystals. This observation is in accordance with our previous report.²⁶ Although several growth experiments were conducted, we could not obtain a BTGS crystal without bubbles. All the grown BTGS crystals were composed of the A₃B₃C₃D₃O₁₄-type single phase. Chemical compositions with the grown crystals were the same as that of the starting powders, which suggested that BTGS melts congruently. Samples were fabricated for further experiments by cutting the crystals while avoiding bubbles.

The positional and anisotropic thermal parameters of BTGS are summarized in Table 2. The common-site multiplicity refinement was conducted assuming the A, B, C, and D sites were occupied by Ba, Ta, Ga, and Si atoms, respectively. This model produced the minimum R value (see Table 1). Therefore, BTGS should have an ordered

| Table 1 | Crystal data and intensity collection for Ba₃Ta₂Ga₂Si₉O₁₄ |
|---------|---------------------------------------------------------|
| Color   | Colorless                                               |
| Diameter of specimen (mm) | 0.130 |
| Crystal system | Trigonal |
| Space group | P321 (No.150) |
| Lattice parameters | a = 8.515 (2) Å, c = 5.192 (1) Å |
| Volume (Å³) | 326.03 |
| Formula weight | 1082.31 |
| Calculated density (g/cm³) | 5.514 |
| Radiation | Mo Kα |
| Monochromator | Graphite [002] |
| μ (Mo Kα) (mm⁻¹) | 2.353 |
| Maximum 2θ (°) | 35 |
| No. of reflections measured | 610 |
| No. of independent reflections | 565 |
| No. of used reflections | 560 |
| | [F² ≥ 4σ(F²)] |
| R | 0.018 |
| Rw | 0.043 |
| Goodness of fit | 1.162 |
structure. The average Ba–O distance is 2.797 Å, and this value is close to that (2.790 Å) of Ba3NbGa3Si2O14.25) The average Ta–O, Ga–O, and Si–O distances are 1.981, 1.849, and 1.633 Å, respectively. These values are the same as those in Ca3TaGa3Si2O14 (CTGS)31) and STGS.22) This result suggests that ionic size in the A site affects physical properties.

All the evaluated material constants of the BTGS crystal are shown in Table 3. In relation to the piezoelectric constants d11 and d14, we found the dependence of the piezoelectric constant on the alkali earth elements occupying the A site in CTGS, STGS, and BTGS crystals. The d11 and d14 values are 4.58 and −10.43 pC/N for CTGS,32) and 4.9 and −3.2 pC/N for STGS,33) respectively. In Refs. 34), 35), it is also reported that the piezoelectric constants d11 and d14 increase and decrease with the increasing ionic radius of a rare-earth element occupying the A site in Ln2Ga3Si2O14 (Ln = La, Pr, and Nd). The dependence of the piezoelectric constants, d11, on the lattice parameter, a, in the langasite-type crystals is shown in Fig. 2. The d11 data were obtained from the literature (LGS,36) LTG,36) CTGS,2) STGS,33) Ca3NbGa3Si2O14,37) Ca3TaAl3Si2O14,38) La3Ga5Si2O14,36) La3GaSiGeO4,20) Ca3Ga2Ge4O14,20) Pr5Ga3Si4O14,14) Nd5Ga3Si2O14,35) Na2CaGe2O5,21). From the figure, an increase in the lattice parameter, a, leads to an increase in the piezoelectric constants, d11. This tendency is explained in the Ref. 24). Increasing the lattice parameter, a implies enlarging the size of the polyhedra composed of a cation and the nearest oxygens along the a-axis. The d11 constants of the crystal with trigonal symmetry indicates a magnitude of electric charge developed by the applied stress along the crystallographic a-axis. By such enlargement, the cations can move more easily within the crystal. This explanation is not universal because there is a different inclination between crystals with the ordered and disordered structures as shown in Fig. 2, nevertheless it is reliable.

In this study, we attempted to understand the detailed relationship between crystal structure and piezoelectric constant in CTGS, STGS, and BTGS crystals with the ordered structure. Langasite-type crystals have the structure in which the A–B site layer and C–D site layer are stacked alternately along the c direction [Fig. 3(a)]. The result and data22,31) of crystal structure analysis indicate

| Table 2. Atomic parameters of Ba3TaGa5Si2O14 with estimated standard deviations in parentheses |
|---------------------------------|---------|---------|---------|---------|---------|---------|
| Atom   | Site  | x       | y       | z       | U(11)  |
|--------|-------|---------|---------|---------|---------|
| Ba     | 3e    | 0.4321(2) | 0       | 0       | 0.0091(1) |
| Ta     | 1a    | 0       | 0       | 0       | 0.0069(1) |
| Si     | 2d    | 1/3     | 2/3     | 0.4817(5) | 0.0063(4) |
| Ga     | 3f    | 0.7452(1) | 0       | 1/2     | 0.0075(2) |
| O1     | 2d    | 1/3     | 2/3     | 0.790(1)  | 0.0111(1) |
| O2     | 6g    | 0.4749(6) | 0.2992(7) | 0.6440(8) | 0.0112(8) |
| O3     | 6g    | 0.2170(6) | 0.1068(7) | 0.2247(7) | 0.0128(7) |

| Table 3. Material constants of Ba3TaGa5Si2O14 single crystal by resonance and antiresonance method |
|-----------------|---------|---------|---------|---------|---------|
| Elastic compliance consts. [10−12 m²/Pa] | s11   | 9.10   | s12   | −1.69   | s23   | −3.54  |
|                 | s33   | 0.72   | s44   | 5.75    | s55   | 19.2   |
| Piezoelectric constants [pC/N] | d11   | 5.80   | d14   | −1.07   |
| Relative dielectric constants [−] | μ11/ε0 | 11.97 | μ13/ε0 | 12.97 |

Fig. 2. Piezoelectric constants, d11, versus the lattice parameter a in the langasite-type crystal. The numbers with the symbols correspond to the following langasite-type crystals; 1: Ba3TaGa3Si2O14,2 : Sr3TaGa3Si2O14,33) 3: Ca3TaGa3Si2O14,4 : Ca3NbGa3Si2O14,5 : Ca3TaAl3Si2O14,6 : La3Ga5Si2O14,7 : La3Ga5Ta2O14,8 : La3Ga5GeO4,9 : La3GaSiO4,10 : Ca3Ga2Ge4O14,11 : Pr5Ga3Si4O14,12 : Nd5Ga3Si2O14,13 : Na2CaGe2O5,21).
that the fractional coordinate $z$ of Si at the $D$ site increases significantly and the angle $O_1$–Si–$O_2$ decreases as the ionic radius of $A$ site atoms increases in these crystals. As mentioned above, the average Si–O distance is the same in the CTGS, STGS, and BTGS crystals. From these observations, it was concluded that a higher ionic radius of $A$ site atoms leads to deform the tetrahedron shape, which is constructed by one $O_1$ and three $O_2$ surrounding the Si, so it is short along the $c$ direction and long normal to the $c$ direction [Fig. 3(b)]. This indicates that the change of the lattice constant $a$ is higher than of lattice constant $c$ in the crystals with the ordered structure. This is proved from the results that the $c/a$ ratio decreases with increasing the ionic radius of the $A$ site atoms ($c/a = 0.615, 0.612, \text{and } 0.609$ for CTGS, STGS, and BTGS, respectively), whereas both the lattice constants $a$ and $c$ increase. There is a spacious room in the $C$–$D$ site layer, therefore, Ga and Si atoms in the $C$–$D$ site layer are displaced when stress is applied and the piezoelectric constant $d_{11}$ is high. In respect to the $d_{14}$, the applied stress direction to crystal lattice is not simply explained and the discussion is still not conclusive.

**Figure 4** shows the temperature dependence of a piezoelectric constant $d_{11}$ of the BTGS crystal. The piezoelectric constant $d_{11}$ of the other langasite-type crystals are also plotted for comparison.$^{2,38-40}$ In this figure, the relative piezoelectric constant $d_{11}$* represents the ratio of the $d_{11}$ value at the measurement temperature and at room temperature ($25^\circ\text{C}$). The $d_{11}$* values increased with the temperature among all the langasite-type crystals. This was because the elastic compliance $s_{11}$* increased with increasing temperature. The BTGS crystal shows a relatively low change in $d_{11}$* value with a temperature of approximately 190 ppm/$^\circ\text{C}$. This change is the lowest in the crystals with the ordered structure.

**Figure 5** shows the temperature dependences of the electric resistivity $\rho$ of as-grown BTGS crystals along the crystallographic $a$-axis. The data of the other langasite-type crystals shown in Fig. 4 are also plotted for comparison.$^{2,38-40}$ We measured the $\rho$ values of the BTGS crystal until 600 $^\circ\text{C}$. This was because the BTGS crystal reacted with electrode Ag–Pd metals used for measurement over 600 $^\circ\text{C}$. More appropriate metals are required for resistivity measurement in higher temperature. The plots of $\ln\rho$ versus 1000/$T$ show linear behavior as presented and $\rho$
The BTGS crystal has $\rho$ values of two orders of magnitude higher than the crystals with the disordered structure. This value is the same level that was reported for GaPO$_4$\textsuperscript{12} and the langasite-type crystals with the ordered structure.\textsuperscript{2,3} The $\rho$ value of BTGS is higher than of LTG, and Al-substituted LTG crystals,\textsuperscript{30} which are the most promising materials. The temperature dependence of the resistivity obeys the Arrhenius equation of the form,

$$\rho = \rho_0 \exp(E_a/k_0 T)$$

where $\rho_0$ is the resistivity at infinite temperature, $E_a$ is the activation energy, $k_0$ is Boltzmann’s constant, and $T$ is the absolute temperature. In BTGS, the activation energy values $E_a$ were found to be 1.14 eV along the crystallographic $a$-axis. This value is higher (0.79–0.87 eV\textsuperscript{39,40}) than for the langasite-type crystals with the disordered structure and comparable to those (1.26 eV\textsuperscript{2}) of the CTGS crystal with the ordered structure. The BTGS crystal has an alternative promising material to apply high-temperature piezoelectric sensors.

4. Summary

The piezoelectric BTGS single crystals were grown by the Cz method. The results of a single-crystal X-ray structure analysis indicated that the cation distribution on each site in BTGS is the same as the other langasite-type crystals with the ordered structure. Using the grown crystals, all material constants of the BTGS crystals were evaluated. The determined piezoelectric constants $d_{11}$ increased with the decreasing ionic radius of the alkali earth element occupying the $A$ site in CTGS, STGS, and BTGS crystals. The temperature dependence of $d_{11}$ was comparable to that of LTG and LTGA. Because of the high-temperature stability of their resistivity and piezoelectric properties, the BTGS crystal is found to be an alternative promising material to apply high-temperature piezoelectric sensors.

Acknowledgments We would like to thank Mr K. Kawasaki of TDK corporation, Japan, for his helpful suggestions in the crystal growth process. Parts of this study were financially supported by the Grants-in-Aid for Scientific Research program of the Japan Society for the Promotion of Science (JSPS KAKENHI, grant number 19H02797).

References

1) S. Zhang, A. Yoshikawa, K. Kamada, E. Frantz, R. Xia, D. W. Snyder, T. Fukuda and T. R. Shrou, Solid State Commun., 148, 213–216 (2008).
2) S. Zhang, Y. Zheng, H. Kong, J. Xin, E. Frantz and T. R. Shrou, J. Appl. Phys., 105, 114107 (2009).
3) Y. Ohashi, T. Kudo, Y. Yokota, Y. Shojo, S. Kurosawa, K. Kamada and A. Yoshikawa, Electron. Lett., 51, 1957–1958 (2015).
4) X. Fu, E. G. Villora, Y. Matsushita, Y. Kitanaka, Y. Noguchi, M. Miyayama, K. Shimamura and N. Ohashi, J. Ceram. Soc. Jpn., 124, 523–527 (2016).
5) S. Zhang, Y. Fei, E. Frantz, D. W. Snyder, B. H. T. Chai and T. R. Shrou, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 55, 2703–2708 (2008).
6) F. Yu, S. Zhang, X. Zhao, D. Yuan, L. Qin, Q. M. Wang and T. R. Shrou, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 58, 868–873 (2011).
7) P. W. Kreml, G. Schleinzer and W. Wallnöfer, Sensor. Actuat. A-Phys., 61, 361–363 (1997).
8) H. Thanner, P. W. Kreml, W. Wallnöfer and P. M. Worsch, Vaccum, 67, 687–691 (2002).
9) H. Takeda, M. Hagiwara, H. Noguchi, T. Hoshina, T. Takahashi, N. Kodama and T. Tsurumi, J. Appl. Phys. Lett., 102, 242907 (2013).
10) C. Shen, S. Zhang, W. Cao, J. Wang, H. Cong, H. Yu and H. Zhang, J. Appl. Phys., 117, 064106 (2015).
11) H. Takeda, K. Yoshida, H. Okudera, K. Lebbou, T. Hoshina and T. Tsurumi, J. Ceram. Soc. Jpn., 125, 23–26 (2017).
12) T. Oshima, T. Hoshina, T. Tsurumi, K. Lebbou and H. Takeda, J. Ceram. Soc. Jpn., 128, 300–305 (2018).
13) Y. Ooiishi, K. Kishi, M. Akiyama, H. Noma, T. Tabaru and D. Nishijima, J. Ceram. Soc. Jpn., 114, 657–659 (2006) [in Japanese].
14) M. Akiyama, T. Kamohara, K. Kano, A. Teshigahara, Y. Takeuchi and N. Kawahara, Adv. Mater., 21, 593–596 (2009).
15) M. Bickermann, B. M. Epelbaum, O. Filip, B. Tautz, P. Heimann and A. Winnacker, Phys. Status Solidi C, 9, 449–452 (2012).
16) R. Radhakrishnan Sumathi, CrystEngComm, 15, 2232–2240 (2013).
17) J. Bohm, R. B. Heimann, M. Hengst, R. Roever and J. Schindler, J. Cryst. Growth, 204, 128–136 (1999).
18) S. Uda, S. Q. Wang, N. Konishi, H. Inaba and J. Harada, J. Cryst. Growth, 237–239, 707–713 (2002).
19) Z. Wang, X. Cheng, D. Yuan, L. Pan, S. Guo, D. Xu and M. Lv, J. Cryst. Growth, 249, 240–244 (2003).
20) E. L. Belokoneva and V. B. Mill, “Crystal chemical systematics of minerals” Ed. by Moscow State Univ., Moscow (1985) p. 140.
21) H. Takeda, R. Uecker, M. Kumatoriya, K. Shimamura, P. Reiche and T. Fukuda, Cryst. Res. Technol., 32, 939–945 (1997).
22) H. Takeda, J. Sato, T. Kato, K. Kawasahi, H. Morikoshi, K. Shimamura and T. Fukuda, Mater. Res. Bull., 35, 245–252 (2000).
23) V. I. Chani, K. Shimamura, Y. M. Yu and T. Fukuda, Mater. Sci. Eng., R, 20, 281–338 (1997).
24) H. Takeda, H. Nakao, S. Izukawa, H. Shimizu, T. Nishida, S. Okamura and T. Shiosaki, J. Alloy. Compd., 408–412, 474–479 (2006).
25) H. Takeda, T. Nishida, S. Okamura and T. Shiosaki, Trans. Mater. Res. Soc. Jpn., 28, 181–184 (2003).
26) H. Takeda, S. Izukawa, S. Okamura and T. Shiosaki, Key Eng. Mat., 269, 23–26 (2004).
27) Y. Zheng, J. Xin, H. Kong, H. Chen and E. Shi, J. Cryst. Growth, 310, 2284–2287 (2008).
28) G. M. Sheldrick, Acta Crystallogr. C, 71, 3–8 (2015).
29) IEEE Standard on Piezoelectricity, “IEEE Standard on Piezoelectricity,” ANSI/IEEE Std 176 (1987).
30) T. Ikeda, “Fundamentals of Piezoelectricity”, Oxford Science, Oxford (1990).
31) A. A. Klimenkova, B. A. Maximov, V. N. Molchanov, B. V. Mill’, M. H. Rabdanov, Yu. V. Pisarevsky and D. Yu. Pushcharovsky, Crystallogr. Rep., 52, 215–220.
32) F. P. Yu, D. R. Yuan, S. J. Zhang, X. Zhao, S. Y. Guo and X. L. Duan, *J. Phys. D Appl. Phys.*, 42, 085112 (2009).
33) X. Shi, D. Yuan, X. Yin, A. Wei, S. Guo and F. Yu, *Solid State Commun.*, 142, 173–176 (2007).
34) J. Sato, H. Takeda, H. Morikoshi, K. Shimamura, P. Rudolph and T. Fukuda, *J. Cryst. Growth*, 191, 746–753 (1998).
35) H. Takeda, S. Izukawa, H. Shimizu, T. Nishida, S. Okamura and T. Shiosaki, *Trans. Mater. Res. Soc. Jpn.*, 30, 63–66 (2005).
36) J. Bohm, E. Chilla, C. Flannery, H. J. Frohlich, T. Hauke, R. B. Heimann, M. Hengst and U. Straube, *J. Cryst. Growth*, 216, 293–298 (2000).
37) T. Karaki, R. Sato, M. Adachi, J. Kusibiki and M. Arakawa, *Jpn. J. Appl. Phys.*, 43, 6721–6724 (2004).
38) X. Fu, E. G. Villora, Y. Matsushita, Y. Kitanaka, Y. Noguchi, M. Miyayama, K. Shimamura and N. Ohashi, *J. Cryst. Growth*, 501, 38–42 (2018).
39) H. Takeda, J. Yamura, T. Hoshina and T. Tsurumi, *J. Ceram. Soc. Jpn.*, 118, 706–710 (2010).
40) H. Takeda, J. Yamura, T. Nishida, T. Hoshina and T. Tsurumi, *Cryst. Res. Technol.*, 50, 944–949 (2015).