Epitaxy of Tin Dioxide on Titanium Dioxide by Mist Chemical Vapor Deposition

Thant Zin Win¹, Katsuhiko Inaba², Shintaro Kobayashi³,
Yuki Kanetake¹, and Yusui Nakamura^{1,4*}

¹ GSST, Kumamoto University, 2-39-1, Kurokami, Chuo-ku, Kumamoto 860-8555, Japan

² X-ray Res. Lab., Rigaku Corporation, 3-9-12, Matsubara, Akishima 196-8666, Japan

³ Appl. Lab., Rigaku Corporation, 3-9-12, Matsubara, Akishima 196-8666, Japan

⁴ FAST, Kumamoto University, 2-39-1, Kurokami, Chuo-ku, Kumamoto 860-8555, Japan

* Corresponding author: Fax: 81-96-342-3842, and e-mail: yusui@cs.kumamoto-u.ac.jp

Tin dioxide (SnO₂) films were epitaxially grown on *m*-plane sapphire and (001) plane titanium dioxide (TiO₂) substrates using mist chemical vapor deposition. The quality of SnO₂ film was evaluated by full width at half maximum (FWHM) of X-ray diffraction (XRD) ω -rocking curve. The lowest value of FWHM was 0.06° for the SnO₂ film on TiO₂ substrate, which was lower than the other reported values. Not only vertical lattice constant but also lateral one were measured by XRD reciprocal space mapping (RSM) and transmission electron microscopy (TEM). Then, the lattice constants of the SnO₂ film on TiO₂ substrate were the same as those of the bulk SnO₂. From the results of TEM and electron backscattering diffraction (EBSD) observations, the quality of the SnO₂ film was higher at upper portion of the SnO₂ film. These results indicated that high-quality single crystal SnO₂ film was formed on TiO₂ substrate.

Key words: hetero-epitaxy, X-ray diffraction, rocking curve, tin oxide, mist-CVD

1. INTRODUCTION

Tin dioxide (SnO₂) is a multipurpose semiconductor with high transparency, physical and chemical stabilities, and excellent electrical properties. Recently SnO₂ is used for gas sensors and transparent conducting films [1-7]. On the other hand, SnO₂ with rutile structure has been attracted much attention for several applications such as power devices, optical devices, and thin-film transistors due to its wide bandgap (3.60 ~ 3.99 eV), high exciton binding energy (0.13 eV), and high electron mobility (250 cm²V⁻¹s⁻¹) [8-15]. In order to apply to commercial devices with high reliability, it is necessary to form the high-quality SnO₂ single crystal. For example, Schottky barrier diode can be formed with a structure of high-quality non-doped SnO₂ film on n-type TiO₂ substrates.

Currently, there are many reports on SnO₂ film deposition using various techniques such as molecular beam epitaxy (MBE), metal-oxide chemical vapor deposition (MOCVD), sputtering, vacuum evaporation, atomic layer deposition (ALD), and others [16-28]. However, there are only several articles on formation of SnO₂ single crystal with high quality. With the help of vacuum techniques such as MBE, MOCVD, and ALD, SnO₂ single crystals were formed on *m*-plane and *r*-plane sapphire substrates. However, the crystal quality was not very high, where full widths at half maximum (FWHMs) of X-ray diffraction (XRD) ω -rocking curve of SnO₂ films were 0.20° to 1.60° [9, 19, 21, 26]. Furthermore, SnO₂ single crystals on titanium dioxide (TiO₂) substrates were reported also using vacuum techniques, but the FWHM values were 0.48° to 0.61°, and thus, the improvement is still necessary [16, 29, 30]. On the other hand, SnO₂ can be grown using an inexpensive technique such as mist chemical vapor deposition (mist-CVD), which can be

operated at atmospheric pressure without vacuum systems [31, 32]. Additionally, mist-CVD system is easy to operate safely, and is environmental friendly technique. Furthermore, high-quality single crystal oxide films such as ZnO, Ga₂O₃, and ZnS/ZnO heterostructure have been grown using mist-CVD [33-35].

Although various techniques including mist-CVD are available for SnO₂ film, there are some difficulties to grow the high-quality epitaxial SnO₂ thin film, due to the lattice mismatch between SnO₂ thin film and the substrates. Recently, the growth of SnO₂ single crystal films on various substrates such as *r*-plane, *a*-plane, and *m*-plane sapphire have been reported [36-39].

In this paper, we report high-quality SnO₂ single crystal films formed on *m*-plane sapphire and (001) plane TiO₂ substrates by mist-CVD. The quality of SnO₂ film was evaluated by FWHM of XRD ω -rocking curve.

2. EXPERIMENTAL PROCEDURES

The SnO₂ films were grown on both low-cost sapphire substrate and relatively high-cost TiO₂ substrate using mist-CVD with tin acetate (Sn(CH₃COO)₄) aqueous solution of 0.04 mol/L. In case of this solution, it was possible to grow high-quality SnO₂ films in our previous study [40, 41]. The surface orientation of the sapphire substrate (50 mm-diameter circular shape) was *m*-plane because the lattice mismatch of the SnO₂ (001) planes and the *m*-plane sapphire is less compared to other sapphire planes. In this growth, three small square lattices of SnO₂ (001) plane are expected to be formed on one large rectangle lattice of *m*-plane sapphire, namely domain matching epitaxy [36, 42, 43]. In case of TiO₂ substrate (10 mm square shape), the surface orientation was (001) plane and the crystal structure was rutile, which are the same as the SnO₂ films. The TiO₂ substrate was cleaned

with an ultrasonic cleaner using the solutions of acetone, ethanol, and deionized water for three times with the duration of two minutes. After the cleaning, SnO₂ films were grown by mist-CVD. The detailed growth conditions were described in Table I.

Table I. Growth conditions of SnO₂ films by mist-CVD

Source solution	Tin acetate (Sn(CH ₃ COO) ₄) aqueous solution (0.04 mol/L)	
Substrate	Sapphire	Titanium dioxide (TiO ₂)
Temperature	650 °C	
Flow rate	3 L/minute (Carrier gas: N ₂)	
Growth rate	1.1 μm/h	1.0 μm/h

After the growth, the surface morphology of these SnO₂ films was observed by field emission scanning electron microscopy (FE-SEM, JSM-7600F, JEOL). The thickness of SnO₂ films was measured by cross-sectional SEM observation because it was unable to etch the SnO₂ film. Then, the crystal quality of SnO₂ films was analyzed by high-resolution XRD (9 kW, CuKα₁, λ=0.154059 nm, Smartlab, Rigaku), where Ge 220 two-bounce monochromator-collimator device was used as the incident optics system. Degree of relaxation of SnO₂ lattice due to epitaxial constraint on TiO₂ substrate was characterized by the reciprocal space mapping (RSM) of XRD. Then, the cross-section of the sample was observed by high-resolution transmission electron microscopy (HR-TEM, 200 kV, JEM-2100plus, JEOL) and electron backscatter diffraction (EBSD, NB5000, Hitachi). The micron-size samples (100 nm-thick, 10 μm-width, 10 μm-height) were formed for cross-sectional TEM analysis by etching the SnO₂ films with focus ion beam (FIB, NB5000, Hitachi).

3. RESULTS AND DISCUSSION

The SEM images of SnO₂ films on *m*-plane sapphire and (001) TiO₂ substrates are shown in Fig. 1. The surface morphologies of the SnO₂ films have many bright lines and dark spots. Thus, we measured the surface roughnesses by atomic force microscopy. The roughnesses of the SnO₂ surfaces on sapphire and TiO₂ substrates were 7.4 nm and 7.9 nm in root mean square (RMS), respectively. These values were smaller than the case of SnO₂ film (RMS: 29 nm) formed on sapphire using tin chloride solution in our previous study [40].

Fig. 1. Surface SEM images; (a) 5 μm-thick SnO₂ film on *m*-plane sapphire, (b) 4 μm-thick SnO₂ film on TiO₂. Cross-sectional SEM images; (c) and (d) corresponding to (a) and (b), respectively.

From the cross-sectional SEM observation, thicknesses of the SnO₂ films were 5 μm on the sapphire substrate, and 4 μm on the TiO₂ substrate, respectively. The reason of forming thick SnO₂ (4 μm) on the TiO₂ substrate was to investigate thickness dependence of the crystal quality. Thus, we measured the crystal quality with Kernel average misorientation (KAM) values for each vertical position from the interface of SnO₂ and TiO₂ as mentioned later.

The thickness distribution of the SnO₂ film on TiO₂ is shown in Fig. 2. The thickness was about 4 μm and almost uniform over 5 mm on the sample.

Fig. 2. Thickness distribution of SnO₂ film on TiO₂ substrate

To characterize the SnO₂ films, XRD θ -2 θ scan was performed as shown in Fig. 3. The 002 reflection peaks of SnO₂ films formed on sapphire and TiO₂ substrates were clearly observed. In addition, 30-30 reflection peak of sapphire substrate and 002 reflection peak of TiO₂ substrate were also observed. From this result, SnO₂ films were grown with [001] orientation both on sapphire and TiO₂ substrates.

Fig. 3. XRD θ -2 θ patterns of SnO₂ film on sapphire and TiO₂ substrates

To quantitatively evaluate crystal quality of the SnO₂ films, XRD ω -rocking curves were measured as shown in Fig. 4, where the FWHMs of SnO₂ films on sapphire and TiO₂ substrates were as narrow as 0.09° and 0.06°, respectively. These results demonstrated that our growth method and the conditions were much better than other growth methods with the vacuum systems. Especially in cases of the SnO₂ films on TiO₂ substrate, the FWHMs were narrower and also the intensities were higher than

those on sapphire substrate. It showed that the SnO₂ film grown on TiO₂ had higher quality. This is because SnO₂ and TiO₂ have the same crystal structure of rutile, and the lattice mismatches between SnO₂ and TiO₂ (+3.1% in both [100] and [010] orientations) are smaller than those between SnO₂ and *m*-plane sapphire (+9.46% in [0001] orientation and -0.42% in [11-20] orientation).

Fig. 4. XRD ω -rocking curves of SnO₂ film on sapphire and TiO₂ substrates

Fig. 5. XRD ϕ -scan of SnO₂ film on TiO₂ substrate

To identify lateral crystal alignment of the SnO₂ film grown on TiO₂ substrate, XRD ϕ -scan was performed as shown in Fig. 5. The (101) planes were used as monitoring planes for both SnO₂ film and TiO₂ substrate, where χ -axis of the sample was tilted at 33.9° and 32.8° for SnO₂ film and TiO₂ substrate, respectively. Four peaks evenly spaced with 90° were observed for (101) planes for both SnO₂ film and TiO₂ substrate, and peak positions of SnO₂ film corresponded to those of TiO₂ substrate. Therefore, SnO₂ film and TiO₂ substrate have four-fold symmetry in the [001] orientation. From the results of XRD θ -2 θ and ϕ scans, it was indicated that the SnO₂ film was single crystal, and the epitaxial orientation relationship was (001) [100] SnO₂ $\parallel$ (001) [100] TiO₂.

The crystal alignment and epitaxial relationship was also verified by XRD reciprocal space map (RSM) measurement with scintillation counter (SC) as shown in Fig. 6. Before the measurement, we adjusted the (001) plane of the TiO₂ substrate. From the RSM, the lattice constants were calculated by the following equation:

$$q = 1/d = 2\sin(\theta_B)/\lambda \quad (1)$$

where q is a distance from the origin in reciprocal space coordinates, d is an interplanar distance, λ is the wavelength of X-ray, and θ_B is Bragg angle. The XRD peak of the SnO₂ film was stronger than the TiO₂ substrate peak because of thick SnO₂ film with thickness of 4 μm . Symmetric 002 reflections for both SnO₂ film and TiO₂ substrate were observed at the alignment of reciprocal coordinate $q_x = 0$. Hence, (001) plane of SnO₂ film should be parallel to (001) plane of TiO₂ substrate.

Fig. 6. Symmetric RSM data of SnO₂ film on TiO₂ substrate

Generally, a hetero-epitaxial film has strain because of the lattice mismatch between the film and the substrate. Then, not only vertical lattice constant but also lateral one of the SnO₂ film were measured by the XRD RSM measurement for 202 reflections of both the epitaxial SnO₂ film and the TiO₂ substrate. The result of asymmetric data of XRD RSM was shown in Fig. 7. From the 202 reflection peak, the lateral and vertical lattice constants of SnO₂ film were obtained to be $a = 4.73 \text{ \AA}$ (lateral) and $c = 3.19 \text{ \AA}$ (vertical), respectively. Therefore, the lattice constants of the SnO₂ film were the same as those of SnO₂ bulk crystal, which indicated that the strain of the SnO₂ film was relaxed.

Fig. 7. Asymmetric RSM data of SnO₂ film on TiO₂ substrate

To observe crystal defects in the SnO₂ film, HR-TEM was used. The bright field image of the cross-sectional SnO₂ film with (110) plane was shown in Fig. 8. Though there were many defects at the interface of SnO₂ film and TiO₂ substrate, the defects were decreased with the thickness of SnO₂ film.

Fig. 8. Bright field TEM image of SnO₂ film on TiO₂ substrate, where five positions for SAED observation were shown.

The selected area electron diffraction (SAED) patterns at the top area of the SnO₂ film were measured as shown in Fig. 9 using the cross-sectional TEM sample. The lattice constants of SnO₂ film calculated from the SAED patterns at top, middle, and bottom areas in Fig. 8 are 4.72 Å for *a*-axis and 3.18 Å for *c*-axis, which are almost the same as those of SnO₂ bulk crystal.

Fig. 9. SAED pattern at top area of SnO₂ film on TiO₂ substrate

The SAED pattern was measured also at the interface of SnO₂ film and TiO₂ substrate as shown in Fig. 10 (a), and Fig. 10 (b) is the corresponding schematic diagram. From these results including XRD and SEAD, the SnO₂ film was shown to be a single crystal with a rutile structure, and the epitaxial orientation relationship was (001) [100] SnO₂ || (001) [100] TiO₂.

In Fig. 10 (a), reciprocal lattice lengths of TiO₂ were larger than those of SnO₂, since lattice constants of TiO₂ were smaller than those of SnO₂. From the SEAD pattern in Fig. 10 (a), lattice constants were 4.72 Å for *a*-axis and 3.18 Å for *c*-axis of SnO₂ film, which were also almost the same as the values of SnO₂ bulk crystal. These results

clearly showed that strain of SnO₂ film was relaxed not only at the top area of SnO₂ film but also near the interface. Though the critical thickness of SnO₂ film on TiO₂ substrate was not found in literature, it is likely to be several nm as other materials. For example, in case of indium gallium arsenide film on indium phosphide substrate (InGaAs/InP) with a lattice mismatch of +3%, the critical thickness was about 5 nm [44]. As described above, the lattice mismatches between SnO₂ and TiO₂ was also +3.1%. Thus, the transition region of the lattice constant of SnO₂ film is probably very thin (several nm), compared to the SAED observation area of 800 nm (400 nm for SnO₂ area) as indicated with the circle in Fig. 8. Therefore, different SnO₂ lattice constant in the transition region did not seem to be detected.

Fig. 10. (a) SAED pattern at the interface area of SnO₂ film on TiO₂ substrate, (b) Schematic diagram of the SAED pattern of (a)

Fig. 11. Inverse pole figure of SnO₂ film on TiO₂ substrate

The cross-sectional TEM sample was also used for EBSD measurement. The scan step of EBSD was 10 nm using a scan mode of hexagonal grid. Figure 11 shows the cross-sectional mapping of inverse pole figure (IPF) for SnO₂ film, in which only (110) plane was observed. Also

from EBSD data, we analyzed the local misorientation of SnO₂ crystal with KAM using the orientation imaging microscopy (OIM) software as shown in Fig. 12. Usually, the KAM analysis is used to evaluate misorientation angle of each grain in poly-crystal samples, but we used it for our single crystal film. In Fig. 12, blue and green colors correspond to small and large misorientation angles, respectively. Then, the portions with green color corresponded to defect areas in TEM image of Fig. 8.

Fig. 12. Kernel average misorientation map of SnO₂ film on TiO₂ substrate with showing vertical positions from the interface.

Fig. 13. Kernel average misorientation charts for the four positions of SnO₂ film (See Fig. 12).

Using the data of Fig. 12, the misorientation angles were separately obtained for four portions (top, middle 1, middle 2, and bottom) in the cross-section of the SnO₂ film. The KAM charts for the four portions were shown in Fig. 13, where the peak amplitudes of KAM were normalized. Then, the peak angles of KAM were plotted in Fig. 14. The KAM peak angle at the bottom area was 0.30° while the value at the top area was reduced to 0.23°. According to this result, it was shown that the misorientation angles monotonically decreased with the thickness of the SnO₂ film. Therefore, the SnO₂ film grown on TiO₂ substrate was shown to have higher quality at the top area compared to bottom area. However, in this KAM analysis, the angle value can be used only for qualitative discussion and not for quantitative one [45]. Additionally, in case of FWHM in XRD rocking curve, tilt angle of mosaic structure is detected. On the contrary, in case of KAM, not only tilt angle (vertical misorientation), but also twist angle (lateral misorientation) are detected. Thus, the angles of KAM (0.23-0.30°) should be larger

than FWHM (0.06°) of rocking curve, and quantitative comparison is not possible.

Fig. 14. Peaks of Kernel average misorientation for vertical positions from the interface of SnO₂ and TiO₂.

4. CONCLUSION

The high-quality SnO₂ films were grown on sapphire and TiO₂ substrates by mist-CVD using Sn(CH₃COO)₄ aqueous solution. The narrow FWHM of XRD ω -rocking curve was obtained to be 0.06° on TiO₂ substrate, which is narrower than other reported values. The SnO₂ film grown on TiO₂ had better quality than those on sapphire because of smaller lattice mismatch. Using RSM of XRD and electron diffraction of TEM, the lattice constants of the SnO₂ film were measured. The results of the lattice constants were almost the same as the bulk SnO₂ from the interface of the film and substrate to the surface of the film. Although there were many defects at the interface in TEM image, the defects were decreased with the film thickness. By EBSD analysis, the Kernel average misorientation angles were measured for several vertical positions in the cross-section of the SnO₂ film. Then, the misorientation angles were monotonically decreased from the interface to the surface. This result corresponded to the decrease of the defects in TEM image.

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REFERENCES

- [1] P. Karthick, D. Vijayanarayanan, M. Sridharan, A.K. Ananth, C. Sanjeeviraja, and K. Jeyadheepan, *Thin Solid Films*, **631**, 1–11 (2017).
- [2] S. Wu, Y. Li, J. Luo, J. Lin, Y. Fan, Z. Gan, and X. Liu, *Opt. Express*, **22**, 4731 (2014).
- [3] V. Fauzia, M.N. Yusnidar, L.H. Lalasari, A. Subhan, and A.A. Umar, *J. Alloys Compd.*, **720**, 79–85 (2017).
- [4] K. Suematsu, W. Harano, T. Oyama, Y. Shin, K. Watanabe, and K. Shimano, *Anal. Chem.*, **90**, 11219–11223 (2018).
- [5] N.S. Subramanian, B. Santhi, T. Sornakumar, G.K. Subbaraj, C. Vinoth, and G. Murugan, *Ionics*, **10**, 273–282 (2004).
- [6] C. Sankar, V. Ponnuswamy, M. Manickam, R.

- Mariappan, and R. Suresh, *Appl. Surf. Sci.*, **349**, 931–939 (2015).
- [7] N. Barsan, J. Rebholz, and U. Weimar, *Sensors Actuators, B Chem.*, **207**, 455–459 (2015).
- [8] G. T. Dang, T. Uchida, T. Kawaharamura, M. Furuta, A. R. Hyndman, R. Martinez, S. Fujita, R. J. Reeves, and M. W. Allen, *Appl. Phys. Express*, **9**, 041101 (2016).
- [9] T. Oshima, T. Okuno, and S. Fujita, *Jpn. J. Appl. Phys.*, **48**, 120207 (2009).
- [10] O. Bierwagen, M.E. White, M.Y. Tsai, T. Nagata, and J.S. Speck, *Appl. Phys. Express*, **2**, 106502 (2009).
- [11] H. K. Summitt, and N. F. Borrelli, *J. Appl. Phys.*, **37**, 2200 (1966).
- [12] K. D. Mc. Roberts, C. G. Fonstad, D. Hubert, *Phys. Rev. B*, **10**, 5213 (1974).
- [13] V. T. Agekyan, *Phys. Status Solidi*, **43**, 11 (1977).
- [14] K. J. Button, C. G. Fonstad, and W. Dreybrodt, *Phys. Rev. B*, **4**, 4539 (1971).
- [15] J. E. Dominguez, L. Fu, and X. Q. Pan, *Appl. Phys. Lett.*, **81**, 5168 (2002).
- [16] M.Y. Tsai, M.E. White, and J.S. Speck, *J. Cryst. Growth*, **310**, 4256–4261 (2008).
- [17] T. Wang, A. Prakash, E. Warner, W.L. Gladfelter, and B. Jalan, *J. Vac. Sci. Technol. A*, **33**, 020606 (2015).
- [18] S. Hishita, P. Janeček, and H. Haneda, *J. Cryst. Growth*, **312**, 3046–3049 (2010).
- [19] M. E. White, M. Y. Tsai, F. Wu, and J. S. Speck, *J. Vac. Sci. Technol. A*, **26**, 1300–1307 (2008).
- [20] Y.H. Choi, and S.H. Hong, *Sensors Actuators, B*, **125**, 504–509 (2007).
- [21] Z. Zhu, J. Ma, L. Kong, C. Luan, and Q. Yu, *J. Cryst. Growth*, **324**, 98–102 (2011).
- [22] Z.G. Song, F. Ji, J. Ma, T. Ning, X.A. Pei, and Y.L. Tan, *Adv. Mater. Res.*, **79–82**, 759–762 (2009).
- [23] G.P. Choi, Y.J. Park, W.S. Noh, and J.S. Park, *Mater. Sci. Forum*, **449–452**, 997–1000 (2004).
- [24] C. Luan, J. Ma, X. Yu, Z. Zhu, W. Mi, and Y. Lv, *Vacuum*, **86**, 1333–1335 (2012).
- [25] G.-H. Lee, *Mater. Trans.*, **54**, 2159–2161 (2013).
- [26] D.H. Kim, J.H. Kwon, M. Kim, and S.H. Hong, *J. Cryst. Growth*, **322**, 33–37 (2011).
- [27] H.E. Cheng, D.C. Tian, and K.C. Huang, *Procedia Eng.*, **36**, 510–515 (2012).
- [28] D.K. Lee, Z. Wan, J.S. Bae, H.B.R. Lee, J.H. Ahn, S.D. Kim, J. Kim, and S.H. Kwon, *Mater. Lett.*, **166**, 163–166 (2016).
- [29] H. Wakabayashi, T. Suzuki, Y. Iwazaki, and M. Fujimoto, *Jpn. J. Appl. Phys.*, **40**, 6081–6087 (2001).
- [30] S. T. Zhang, J. L. Rouviere, V. Consonni, H. Roussel, L. Rapenne, E. Pernot, D. Munoz-Rojas, A. Klein, and D. Bellet, *Materials and Design*, **132**, 518–525 (2017).
- [31] J. G. Lu, T. Kawaharamura, H. Nishinaka, Y. Kamada, T. Ohshima, and S. Fujita, *J. Cryst. Growth*, **299**, 1–10 (2007).
- [32] T. Kawaharamura, H. Nishinaka, and S. Fujita, *Jpn. J. Appl. Phys.*, **47**, 4669–4675 (2008).
- [33] H. Tanoue, T. Taniguchi, S. Wada, S. Yamamoto, S. Nakamura, Y. Naka, H. Yoshikawa, M. Munekata, S. Nagaoka, and Y. Nakamura, *Appl. Phys. Express*, **8**, 125502 (2015).
- [34] K. Kaneko, H. Kawanowa, H. Ito, and S. Fujita, *Jpn. J. Appl. Phys.*, **51**, 020201 (2012).
- [35] K. Okita, K. Inaba, Z. Yatabe, and Y. Nakamura, *Jpn. J. Appl. Phys.*, **57**, 065503 (2018).
- [36] J.H. Kwon, Y.H. Choi, D.H. Kim, M. Yang, J. Jang, T.W. Kim, S.H. Hong, and M. Kim, *Thin Solid Films*, **517**, 550–553 (2008).
- [37] C. Luan, Z. Zhu, W. Mi, and J. Ma, *Vacuum*, **99**, 110–114 (2014).
- [38] Z. Zhu, J. Ma, C. Luan, L. Kong, and Q. Yu, *Appl. Surf. Sci.*, **257**, 2516–2519 (2011).
- [39] T. Okuno, T. Oshima, S.D. Lee, and S. Fujita, *Phys. Status Solidi C*, **8**, 540–542 (2011).
- [40] Z. Yatabe, T. Tsuda, J. Matsushita, T. Sato, T. Otabe, K. Sue, S. Nagaoka, and Y. Nakamura, *Phys. Status Solidi C*, **14**, 1600148 (2017).
- [41] T. Z. Win, K. Inaba, S. Kobayashi, T. Furukawa, Y. Kanetake, S. Miwa, T. Hashishin, and Y. Nakamura, *Jpn. J. Appl. Phys.*, **59**, 095503 (2020).
- [42] J.W. Lee, J.H. Kim, S.K. Han, S.K. Hong, J.Y. Lee, S.I. Hong, and T. Yao, *J. Cryst. Growth*, **312**, 238 (2010).
- [43] T. Moriyama and S. Fujita, *Jpn. J. Appl. Phys.*, **44**, 7919 (2005).
- [44] K. Koksul, B. Gonul, and M. Oduncuoglu, *Eur. Phys. J. B*, **69**, 211–218 (2009).
- [45] L. Saraf, *Microscopy and Microanalysis*, **17**, 424–425 (2011).

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