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# Triangular radial Nb<sub>2</sub>O<sub>5</sub> nanorod growth on c-plane sapphire for ultraviolet-radiation detection†

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Nb<sub>2</sub>O<sub>5</sub> nanostructures with excellent crystallinities were grown on c-plane sapphire and employed for ultraviolet-(UV)-radiation detection. The triangular radial Nb<sub>2</sub>O<sub>5</sub> grown on the c-sapphire substrate had a 6-fold symmetry with domain matching epitaxy on the substrate. Owing to the radial growth, the nanorods naturally connected when the deposition time increased. This structure can be used as a UV-detector directly by depositing macroscale electrodes without separation of a single nanorod and e-beam lithography process. It was confirmed that electric reactions occur at different UV irradiation wavelengths (254 nm and 365 nm).

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## Introduction

Ultraviolet rays (UV) are electromagnetic waves with shorter wavelengths than those of visible light, mainly in the range of 200 nm to 400 nm.<sup>1</sup> UV irradiation affecting our lives can be divided into two types: (i) generated from the sun, reaching the earth through cosmic radiation, and (ii) those emerging from various chemical reactions on the earth. UV irradiation generated from the sun is mostly absorbed by various molecules in the atmosphere (CO<sub>2</sub>, H<sub>2</sub>O, *etc.*); radiation reaching the surface is in the region of UV-A (320–400 nm).<sup>1</sup> UV-A can have positive effects, such as sterilisation, or side effects such as occurrence of skin cancer. On the other hand, UV radiation generated by various chemical reactions produced by humans varies from UV-A to UV-C (UV-B: 290–320 nm and UV-C: 200–290 nm). Both efficient use of the generated UV radiation and its blockage for safety purposes are important.

In this regard, one of the most important factors is the efficient UV detection. Theoretically, one of the best approaches to detect UV irradiation is to measure changes in electrical conductivity of an UV-irradiated material with band gap.<sup>1–5</sup> It is important to select a material with an appropriate band gap ( $E_g > 3.1$  eV) in order to detect UV radiation in the range of 200 nm to 400 nm (UV-A to UV-C regions). However, if the band gap is

too large, the material is close to insulator and the electron excitation effect due to UV absorption is not sufficient to detect.

In this study, we aimed to implement a UV-radiation detector using Nb<sub>2</sub>O<sub>5</sub> with an ideal band-gap energy in the range of 3.5 eV to 4.8 eV (photon energy of 354 nm to 258 nm)<sup>6–8</sup> and chemical stability<sup>9–11</sup> for UV detection. It has already been shown by Fang *et al.*<sup>12</sup> and Liu *et al.*<sup>13</sup> that Nb<sub>2</sub>O<sub>5</sub> can be used as a UV detector and has high responsivity. In addition, the Nb<sub>2</sub>O<sub>5</sub> UV detector was recently synthesized using a simple and low cost hydrothermal method.<sup>14</sup> In order to develop the UV-detector using Nb<sub>2</sub>O<sub>5</sub>, materials with good crystallinities should be synthesised, as when a defect is present in Nb<sub>2</sub>O<sub>5</sub>, light absorption occurs due to the defect levels (532 nm: 2.3 eV and 808 nm: 1.5 eV). In the case of thin-film or bulk syntheses, the possibility of occurrence of defects such as grain boundaries in the synthesised material increases. We aimed to synthesise nanoscale single-crystal Nb<sub>2</sub>O<sub>5</sub> (various structures of Nb<sub>2</sub>O<sub>5</sub> nanomaterials were used for applications to gas sensors,<sup>15,16</sup> photo-catalysts,<sup>17,18</sup> photo-detectors,<sup>12,19</sup> batteries,<sup>20,21</sup> solar cells,<sup>22,23</sup> *etc.*). In addition, if the detector device is fabricated using a single nanorod,<sup>11,24–28</sup> the fabrication is complex (such as e-beam lithography), leading to a lower productivity and higher process costs. Therefore, in this study, synthesis conditions (substrate type and orientation, precursor of Nb, growth temperature, and reaction/carrier gas) were investigated so that synthesised Nb<sub>2</sub>O<sub>5</sub> nanostructures could be naturally connected to each other to enable to immediately use the device when only macroscale electrodes are deposited.

## Experimental

### Growth of Nb<sub>2</sub>O<sub>5</sub> nanostructures

The growth of Nb<sub>2</sub>O<sub>5</sub> was performed on a single-crystal c-plane sapphire substrate (Namkang Hi-tech Co., Ltd., SaR 100-500)

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using a quartz tube furnace.  $\text{NbCl}_5$  (Alfa Aesar, #11548), used as a Nb precursor, was placed in a stainless-steel canister, which was heated by a heating mantle. The sublimed  $\text{NbCl}_5$  and Ar carrier gas were introduced into the tube through a 1/4 inch stainless-steel gas line, which was wrapped and heated by a commercial heating tape. The temperatures of the canister and line were maintained at 140 °C and 160 °C, respectively.

For cleaning, the sapphire substrates were sonicated in acetone, alcohol, and deionised (DI) water for 15 min in each solvent. The sapphire substrates were then loaded into the tube furnace and the system was pumped down to vacuum and refilled with Ar gas to obtain atmospheric pressure. The furnace temperature was increased to 900 °C within 40 min in Ar environment with an Ar gas flow of 200 sccm. After the temperature reached 900 °C, the growth of  $\text{Nb}_2\text{O}_5$  was initiated by introducing another flow (200 sccm) of Ar carrier gas through the canister to the furnace. After the growth, the Nb-precursor supply line was closed, and the samples were rapidly cooled down under the Ar environment.

### Analysis and measurement

An X-ray diffractometer (Bruker D8-Advance with monochromated  $\text{Cu-K}\alpha_1$  radiation; scan rate of  $0.05^\circ \text{ s}^{-1}$ ) was used for identification of the sample. A pole figure analysis was performed to study the symmetry of the sample using an X-ray diffractometer (PANalytical, X'pert PRO using  $\text{Cu-K}\alpha$  radiation,  $\chi$ : 0–75° and  $\varphi$ : 0–360° at  $2\theta$  of 25°). The surface morphology and cross-section structure of the sample were investigated by SEM (Hitachi, S-4800). Transmission electron microscopy (TEM) (JEOL, JEM-2100F, at 200 kV) was employed to analyse the structures and growth directions of the rods. A UV/visible spectrometer (Shimadzu, UV-3600) was used to measure the optical transmittance of the material. A current–voltage ( $I$ – $V$ ) curve and time-dependent response of the UV detector were obtained using a probe station (MSTECH, MST5000). A single-wavelength (254 nm/365 nm) UV lamp (VILBER, VL-215 LC) was used as the UV source.

## Results and discussion

To understand the effect of the substrate on the growth of the  $\text{Nb}_2\text{O}_5$  nanorods, we performed SEM on  $\text{Nb}_2\text{O}_5$  synthesised on three types of substrates ( $\text{SiO}_2/\text{Si}$ , graphene-coated Ni foil, and  $c$ -plane (0006) sapphire substrate; see Fig. 1a). On the graphene/Ni surface, irregularly sized structures are observed, while on the other two substrates ( $\text{SiO}_2/\text{Si}$  and  $c$ -plane sapphire), nanorods with uniform sizes were synthesised. The irregularities observed on the graphene surface can be interpreted as a phenomenon in which niobium oxide nuclei cannot be easily generated owing to the low surface energy of the graphene surface ( $40\text{--}50 \text{ mJ m}^{-2}$ ) compared to those of  $\text{SiO}_2/\text{Si}$  ( $\sim 800 \text{ mJ m}^{-2}$ ) and  $c$ -plane sapphire ( $\sim 1900 \text{ mJ m}^{-2}$ ).<sup>29–31</sup> X-ray diffraction (XRD) was performed to characterise the nanorod alignments on  $\text{SiO}_2/\text{Si}$  and  $c$ -plane sapphire (Fig. 1b). The  $\text{Nb}_2\text{O}_5$  nanorods deposited on the  $c$ -plane sapphire substrate have a preferential orientation of the monoclinic (–713) plane (Joint Committee on

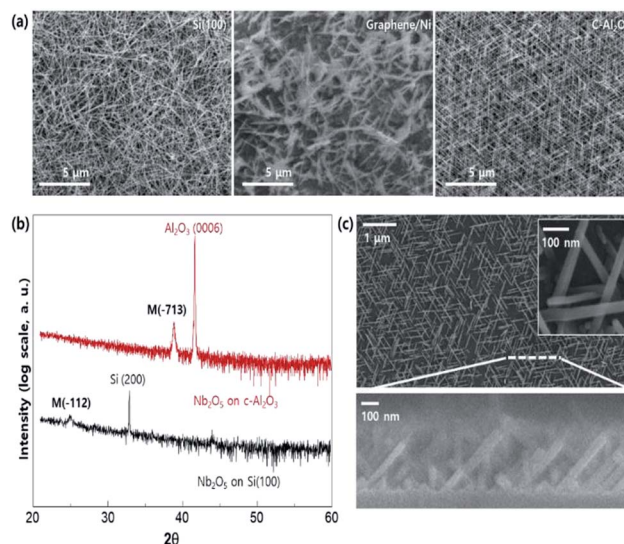


Fig. 1 (a) Scanning electron microscopy (SEM) images of  $\text{Nb}_2\text{O}_5$  nanorods grown for 90 min on different substrates. (b) X-ray diffraction (XRD) patterns of  $\text{Nb}_2\text{O}_5$  on  $c$ -plane sapphire (top) and Si (100) (bottom). (c) SEM images of  $\text{Nb}_2\text{O}_5$  nanorods grown on  $c$ -plane sapphire for 30 min.

Powder Diffraction Standards (JCPDS) no. 37-1468),<sup>32</sup> whereas those on the  $\text{SiO}_2/\text{Si}$  substrate are relatively randomly oriented and have low crystallinities.

SEM images (Fig. 1c) of the sample obtained with a reduced deposition time (Fig. 1a and c show the samples deposited for 90 min and 30 min, respectively) confirm the preferential orientation of  $\text{Nb}_2\text{O}_5$  deposited on the  $c$ -plane sapphire and reveal that equilateral triangular nanostructures were uniformly distributed with a tilting angle of approximately 45° with respect to the substrate.

TEM was performed to understand the regularity of the  $\text{Nb}_2\text{O}_5$  nanorods grown on the  $c$ -plane sapphire crystal. As shown in Fig. 2a and b, the  $\text{Nb}_2\text{O}_5$  nanorod with a (–112) growth direction has a tilting angle of 45.01° with respect to the (–713) plane, which is the preferred orientation, as shown in the XRD measurement (Fig. 2c and 1b). In addition, the result that no metallic component was detected in the head of the  $\text{Nb}_2\text{O}_5$  nanorod reveals that Nb, decomposed from the  $\text{NbCl}_5$  precursor, combines with remaining oxygen in the furnace to form  $\text{Nb}_2\text{O}_5$  directly, referred to as vapour–solid growth mechanism.<sup>33–35</sup>

The X-ray pole figure of the  $\text{Nb}_2\text{O}_5/c$ -sapphire system was measured to understand the triangular arrangement of the nanorods. When the pole figure is measured at a tilting angle ( $\chi$ ) of 55°, the part with a 6-fold symmetry and that with a 3-fold symmetry are mixed, as shown in Fig. 3a and b. The sapphire (102) plane is tilted at 57.6° with respect to the (006) plane (referred to as  $c$ -plane) and has a 3-fold symmetry; therefore, the 3-fold symmetry (green circles in Fig. 3a) corresponds to the sapphire substrate. The remaining structures with the 6-fold symmetry can be attributed to the synthesised  $\text{Nb}_2\text{O}_5$ .  $\text{Nb}_2\text{O}_5$ , which has a monoclinic structure, usually has a 2-fold symmetry; however, it can have a 6-fold



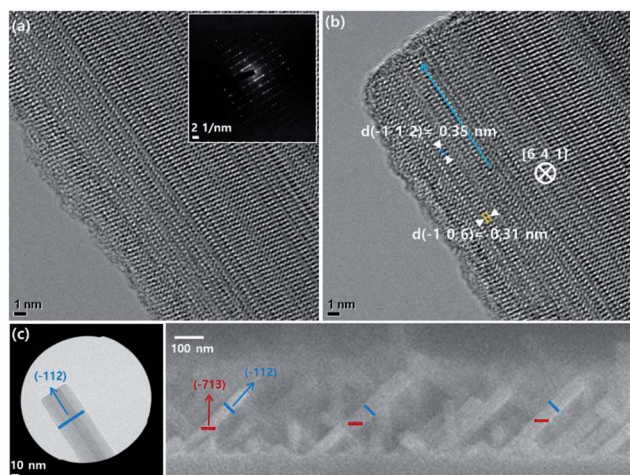


Fig. 2 (a and b) High-resolution TEM images and selected-area electron diffraction (SAED) pattern of a single  $\text{Nb}_2\text{O}_5$  nanorod. The SAED pattern was recorded from the  $\text{Nb}_2\text{O}_5$  nanorod shown in (c). (c) Low-magnification TEM image (left) and cross-section SEM image (right) of a single  $\text{Nb}_2\text{O}_5$  nanorod.

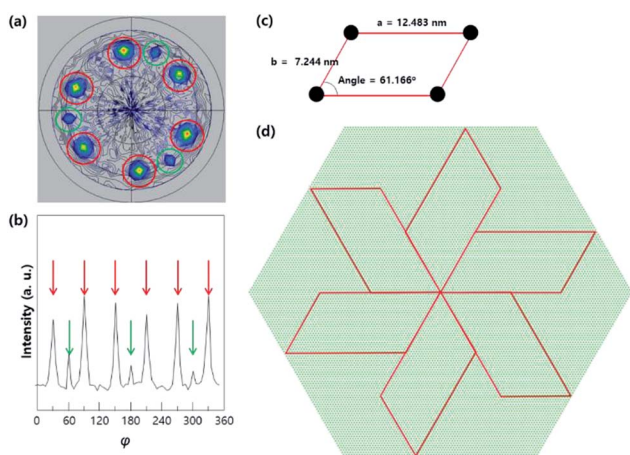


Fig. 3 (a) X-ray pole figure of the  $\text{Nb}_2\text{O}_5/c$ -sapphire system measured at a  $2\theta$  angle of  $25.05^\circ$  for the monoclinic  $\text{Nb}_2\text{O}_5$  ( $-112$ ) peak. Red and green circles represent the peaks of  $\text{Nb}_2\text{O}_5$  nanorods and sapphire substrate, respectively. (b) Azimuthal ( $\phi$ ) scan data measured at a  $\chi$  angle of  $55^\circ$ . (c) Cell shape of the monoclinic  $\text{Nb}_2\text{O}_5$  ( $-713$ ) plane. (d) Schematic of the hexagonal arrangement of the monoclinic  $\text{Nb}_2\text{O}_5$  ( $-713$ ) plane on the  $c$ -sapphire substrate.

symmetry if intervals of  $120^\circ$  are observed. Fig. 3c shows the cell shape of the monoclinic ( $-713$ ) plane of  $\text{Nb}_2\text{O}_5$  ( $a = 12.483$  nm,  $b = 7.244$  nm,  $\alpha = 90^\circ$ , and  $\gamma = 61.166^\circ$ ; the black circles represent O atoms). The epitaxial growth along the  $\text{Nb}_2\text{O}_5$  ( $-713$ ) plane on the  $c$ -plane sapphire substrate with an interatomic distance of 0.275 nm can be explained by domain matching epitaxy (DME).<sup>36–38</sup> The length of 45 atomic spacings of  $\text{Al}_2\text{O}_3$  is 12.375 nm ( $0.275$  nm  $\times$  45 = 12.375 nm), which implies a domain mismatch with the  $\text{Nb}_2\text{O}_5$   $a$ -axis of approximately 0.108 nm, while that of 3 atomic spacings of  $\text{Al}_2\text{O}_3$  is 0.825 nm ( $0.275$  nm  $\times$  3 = 0.825 nm), corresponding to a domain mismatch with the  $\text{Nb}_2\text{O}_5$   $b$ -axis of approximately

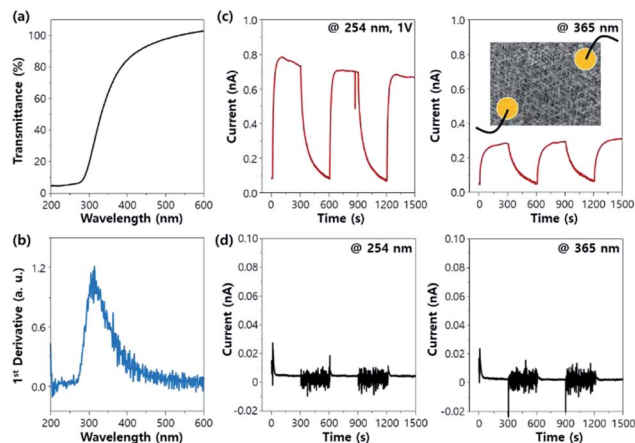


Fig. 4 (a) UV-visible transmittance spectrum of the  $\text{Nb}_2\text{O}_5/c$ -sapphire system and (b) its 1<sup>st</sup> derivative. Photo-conductivity of  $\text{Nb}_2\text{O}_5$  grown on (c)  $c$ -sapphire and (d) Si (100) illuminated with lights with wavelengths of (left) 254 nm and (right) 365 nm at an applied voltage of 1 V.

0.101 nm, leading to the hexagonal arrangement shown in Fig. 3d.

The synthesised triangular radial  $\text{Nb}_2\text{O}_5$  nanorods have excellent crystal qualities, which suggests that they have excellent properties in terms of UV absorption. Fig. 4a shows the UV-visible transmittance of the  $\text{Nb}_2\text{O}_5/c$ -sapphire sample. At approximately 400 nm, the light absorption is approximately 20%; with the decrease in the wavelength, the absorption increases (95% at 280 nm). As shown in the first-order differential form of the transmission spectrum (Fig. 4b), this absorption tendency is most prominent at approximately 300 nm, which implies that the synthesised  $\text{Nb}_2\text{O}_5$  on  $c$ -sapphire can be effectively employed in a wide UV-detection range (from A to C). In addition, we could see the changes in the UV absorption behaviour through the comparison with the UV-visible transmittance spectrum of the sample grown for a longer time (Fig. S1†). As the synthesis time increased, the density of the nanorods increased and the nanorods were more cross-linked as shown in Fig. 1a and b, resulting in the change in the UV transmittance behaviour. Not only did the absolute amount of absorbed light increase, but also the absorption range was up-shifted by approximately 30 nm (see the change of the wavelength at which the slope of the graph changes from positive to negative). Furthermore, the relation of the UV-absorption to the synthesis temperature could also be deduced. As the synthesis temperature was lower, the density of nanorods decreased, and the nanorods were less cross-linked (see Fig. S2†). Based on the relationship between nanorods density and UV-absorption that we have seen above, it can be inferred that the higher the temperature, the greater the amount of UV absorbed.

The triangular radial  $\text{Nb}_2\text{O}_5$  nanorods deposited on the  $c$ -sapphire substrate are connected to each other using a longer deposition time. Therefore, the system can be directly used as a UV-radiation detector without separation of nanorods and e-beam lithography process; *i.e.*, the device can be fabricated by directly depositing macroscale electrodes (shown in the inset



schematics of Fig. 4c at a UV wavelength of 365 nm). In the Nb<sub>2</sub>O<sub>5</sub>/c-sapphire structure, distinct photoreactions are observed at UV wavelengths of 254 nm and 365 nm at an applied constant voltage of 1 V. The shorter UV wavelength provides a larger current (Fig. 4c). The current value increases as the applied voltage increases and has a linear relationship with the applied voltage. Fig. S3† shows the *I*-*V* curve of Nb<sub>2</sub>O<sub>5</sub> grown on c-sapphire while illuminating UV light. The Nb<sub>2</sub>O<sub>5</sub>/Si structure exhibits photo-reactivity; however, the signal is very small, hindering its application as an actual device (Fig. 4d). Through this process, Nb<sub>2</sub>O<sub>5</sub> nanorods with excellent crystallinities and self-connection can be easily employed for UV-radiation detection devices. The spectra responsivity (*R<sub>λ</sub>*) and external quantum efficiency (EQE) are two critical parameters to show the performance of the UV detector.<sup>12</sup> They are expressed as  $R_{\lambda} = \Delta I / PS$  and  $EQE = R_{\lambda} hc / e \lambda$ , respectively, where  $\Delta I$  is the difference between the photo-excited current and dark current, *P* is the light power density, *S* is the irradiated area, *h* is Planck's constant, *c* is the velocity of light, *e* is the electronic charge, and  $\lambda$  is the exciting wavelength. The calculated *R<sub>λ</sub>* and EQE of the Nb<sub>2</sub>O<sub>5</sub> on c-plane sapphire at 1 V are  $1.87 \times 10^{-3} \text{ A W}^{-1}$  and 0.913% when irradiated with 254 nm UV and  $1.76 \times 10^{-4} \text{ A W}^{-1}$  and 0.060% when irradiated by 365 nm UV. These values are difficult to compare with those of the other materials with nanowire (rod) network or mat structure as with ours reported in the literature because they were hardly evaluated by *R<sub>λ</sub>* and EQE values, and even if evaluated, they were evaluated in microscale. These values are usually measured for a single nanowire,<sup>39</sup> nanobelt,<sup>12</sup> and nanoplate<sup>13</sup> between microscale electrodes in the literature. There was one paper that measured *R<sub>λ</sub>* value of Nb<sub>2</sub>O<sub>5</sub> nanomoss structure in macroscale, where the *R<sub>λ</sub>* at 10 V is  $2.43 \times 10^{-3} \text{ A W}^{-1}$  when irradiated with 365 nm UV.<sup>14</sup> Considering that a voltage 10 times higher than the voltage we applied was used, it can be inferred that the increased  $\Delta I$  value due to the higher *V* led to the larger *R<sub>λ</sub>* value than ours. The  $\Delta I$ -*V* relationship for our sample is shown in Fig. S3.† However, the *R<sub>λ</sub>* and EQE values of our sample are significantly smaller than those of single Nb<sub>2</sub>O<sub>5</sub> nanobelt (15.2 A W<sup>-1</sup> with 320 nm at 1 V)<sup>12</sup> and nanoplate (24.7 A W<sup>-1</sup> with 320 nm at 1 V)<sup>13</sup> reported in other articles. Unlike them, our measurements are not on a single nanorod but on interconnected rods between the macroscale electrodes. Therefore, carrier transport must occur not only within nanorods but also between nanorods. In the case of transport between nanorods, carriers must overcome the junction barrier at the interface between the nanorods to move from one nanorod to another.<sup>12,39,40</sup> The low measured values can be attributed to the numerous transport processes that carriers experience when moving through the macroscale channel.

## Conclusions

Nb<sub>2</sub>O<sub>5</sub> nanostructures with excellent crystallinities were grown on c-plane sapphire and their UV-detection performance was measured. The grown Nb<sub>2</sub>O<sub>5</sub> on the c-sapphire substrate had a 6-fold symmetry with DME on the substrate; the results confirmed the radial growth. Owing to the radial growth, the

nanorods naturally connected when the deposition time increased. This structure can be used as a UV-radiation detector directly by depositing macroscale electrodes without separation of a single nanorod and e-beam lithography process. It was confirmed that electric reactions occur at different UV irradiation wavelengths (254 nm and 365 nm). Therefore, it is expected that the structure can be easily employed in the development of a large-area UV sensor.

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

- 1 X. Fang, Y. Bando, U. K. Gautam, T. Zhai, H. Zeng, X. Xu, M. Liao and D. Golberg, *Crit. Rev. Solid State Mater. Sci.*, 2009, **34**, 190–223.
- 2 K.-J. Chen, F.-Y. Hung, S.-J. Chang and S.-J. Young, *J. Alloys Compd.*, 2009, **479**, 674–677.
- 3 H. Wu, Y. Sun, D. Lin, R. Zhang, C. Zhang and W. Pan, *Adv. Mater.*, 2009, **21**, 227–231.
- 4 N. Gogurla, A. K. Sinha, S. Santra, S. Manna and S. K. Ray, *Sci. Rep.*, 2014, **4**, 6483.
- 5 Y. Xie, L. Wei, G. Wei, Q. Li, D. Wang, Y. Chen, S. Yan, G. Liu, L. Mei and J. Jiao, *Nanoscale Res. Lett.*, 2013, **8**, 188.
- 6 J. W. Schultze and M. Lohrengel, *Electrochim. Acta*, 2000, **45**, 2499–2513.
- 7 T. Proslir, J. Zasadzinski, L. Cooley, M. Pellin, J. Norem, J. Elam, C. Z. Antoine, R. A. Rimmer and P. Kneisel, *IEEE Trans. Appl. Supercond.*, 2009, **19**, 1404–1408.
- 8 S. Zhuiykov and E. Kats, *World Academy of Science, Engineering and Technology*, 2013, vol. 78, p. 484.
- 9 R. Jose, V. Thavasi and S. Ramakrishna, *J. Am. Ceram. Soc.*, 2009, **92**, 289–301.
- 10 H. Luo, W. Song, P. G. Hoertz, K. Hanson, R. Ghosh, S. Rangan, M. K. Brennaman, J. J. Concepcion, R. A. Binstead and R. A. Bartynski, *Chem. Mater.*, 2012, **25**, 122–131.
- 11 L. Alibabaei, H. Luo, R. L. House, P. G. Hoertz, R. Lopez and T. J. Meyer, *J. Mater. Chem. A*, 2013, **1**, 4133–4145.
- 12 X. Fang, L. Hu, K. Huo, B. Gao, L. Zhao, M. Liao, P. K. Chu, Y. Bando and D. Golberg, *Adv. Funct. Mater.*, 2011, **21**, 3907–3915.
- 13 H. Liu, N. Gao, M. Liao and X. Fang, *Sci. Rep.*, 2015, **5**, 7716.
- 14 R. Abdul Rani, A. S. Zoofakar, N. S. Khairir, M. H. Mamat, S. Alrokayan, H. A. Khan and M. R. Mahmood, *J. Mater. Sci.: Mater. Electron.*, 2018, **29**, 1–10.



- 15 Z. Wang, Y. Hu, W. Wang, X. Zhang, B. Wang, H. Tian, Y. Wang, J. Guan and H. Gu, *Int. J. Hydrogen Energy*, 2012, **37**, 4526–4532.
- 16 R. A. Rani, A. S. Zolfakar, J. Z. Ou, M. R. Field, M. Austin and K. Kalantar-Zadeh, *Sens. Actuators, B*, 2013, **176**, 149–156.
- 17 K. Sayama, H. Sugihara and H. Arakawa, *Chem. Mater.*, 1998, **10**, 3825–3832.
- 18 H. Kominami, K. Oki, M. Kohno, S.-i. Onoue, Y. Kera and B. Ohtani, *J. Mater. Chem.*, 2001, **11**, 604–609.
- 19 L. Sang, M. Liao and M. Sumiya, *Sensors*, 2013, **13**, 10482–10518.
- 20 H. Nakazawa, K. Sano, T. Abe, M. Baba and N. Kumagai, *J. Power Sources*, 2007, **174**, 838–842.
- 21 B. Reichman and A. J. Bard, *J. Electrochem. Soc.*, 1981, **128**, 344–346.
- 22 M. K. Siddiki, S. Venkatesan and Q. Qiao, *Phys. Chem. Chem. Phys.*, 2012, **14**, 4682–4686.
- 23 O. Wiranwetchayan, Z. Liang, Q. Zhang, G. Cao and P. Singjai, *Mater. Sci. Appl.*, 2011, **2**, 1697.
- 24 C. Soci, A. Zhang, B. Xiang, S. A. Dayeh, D. Aplin, J. Park, X. Bao, Y.-H. Lo and D. Wang, *Nano Lett.*, 2007, **7**, 1003–1009.
- 25 Y. Jiang, W. J. Zhang, J. S. Jie, X. M. Meng, X. Fan and S. T. Lee, *Adv. Funct. Mater.*, 2007, **17**, 1795–1800.
- 26 J.-J. Wang, F.-F. Cao, L. Jiang, Y.-G. Guo, W.-P. Hu and L.-J. Wan, *J. Am. Chem. Soc.*, 2009, **131**, 15602–15603.
- 27 L. Li, X. Fang, T. Zhai, M. Liao, U. K. Gautam, X. Wu, Y. Koide, Y. Bando and D. Golberg, *Adv. Mater.*, 2010, **22**, 4151–4156.
- 28 Y. Zhang, J. Wang, H. Zhu, H. Li, L. Jiang, C. Shu, W. Hu and C. Wang, *J. Mater. Chem.*, 2010, **20**, 9858–9860.
- 29 H. K. Yu and J.-L. Lee, *Sci. Rep.*, 2014, **4**, 6589.
- 30 D. T. Danielson, D. K. Sparacin, J. Michel and L. C. Kimerling, *J. Appl. Phys.*, 2006, **100**, 083507.
- 31 J. Guo, D. Ellis and D. Lam, *Phys. Rev. B*, 1992, **45**, 3204.
- 32 S. Heusing, D.-L. Sun, J. Otero-Anaya and M. A. Aegerter, *Thin Solid Films*, 2006, **502**, 240–245.
- 33 Y. Zhang, N. Wang, S. Gao, R. He, S. Miao, J. Liu, J. Zhu and X. Zhang, *Chem. Mater.*, 2002, **14**, 3564–3568.
- 34 A. Umar, S. Kim, Y.-S. Lee, K. Nahm and Y. Hahn, *J. Cryst. Growth*, 2005, **282**, 131–136.
- 35 Y. L. Chueh, M. W. Lai, J. Q. Liang, L. J. Chou and Z. L. Wang, *Adv. Funct. Mater.*, 2006, **16**, 2243–2251.
- 36 H. K. Yu and J.-L. Lee, *Cryst. Growth Des.*, 2010, **10**, 5200–5204.
- 37 F. Sánchez, R. Bachelet, P. de Coux, B. Warot-Fonrose, V. Skumryev, L. Tarnawska, P. Zaumseil, T. Schroeder and J. Fontcuberta, *Appl. Phys. Lett.*, 2011, **99**, 211910.
- 38 W.-R. Liu, Y.-H. Li, W. Hsieh, C.-H. Hsu, W. Lee, Y. Lee, M. Hong and J. Kwo, *Cryst. Growth Des.*, 2008, **9**, 239–242.
- 39 M. Chen, L. Hu, J. Xu, M. Liao, L. Wu and X. Fang, *Small*, 2011, **7**, 2449–2453.
- 40 S. Jeong, M. W. Kim, Y.-R. Jo, Y.-C. Leem, W.-K. Hong, B.-J. Kim and S.-J. Park, *Nano Energy*, 2016, **30**, 208–216.

