Evolution of crystallographic structure and ferroelectricity of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with different deposition rate

Cite as: AIP Advances 10, 015104 (2020); https://doi.org/10.1063/1.5121454
Submitted: 24 July 2019. Accepted: 26 November 2019. Published Online: 02 January 2020

Taeho Kim, Minho An, and Sang hun Jeon

AVS Quantum Science
A new interdisciplinary home for impactful quantum science research and reviews
NOW ONLINE

© 2019 Author(s).
Evolution of crystallographic structure and ferroelectricity of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with different deposition rate

Taeho Kim, Minho An, and Sanghun Jeon

AFFILIATIONS
1 School of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea
2 Department of Applied Physics, Korea University, 2511, Sejongro, Sejong 339-700, South Korea

ABSTRACT
Hf$_{0.5}$Zr$_{0.5}$O$_2$ films are one of the most attractive HfO$_2$-based ferroelectric films because of good ferroelectricity, extreme thinness, and excellent compatibility with silicon devices. The origin of the ferroelectricity of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films is the noncentrosymmetric orthorhombic phase (space group Pca2$_1$). The effects of process temperature, annealing temperature, thickness, and doping to increase the portion of the orthorhombic phase, which contributes to ferroelectricity, have been studied extensively. However, although most studies have used atomic layer deposition, no study has been reported on the effect of the deposition rate on the ferroelectricity of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films. In this work, the influences of the deposition rate on the ferroelectricity and crystal structure of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films were examined. In order to conduct systematic and quantitative analysis, measurements of switching transient current, ferroelectric P-E curve, dielectric constant, deconvolution of grazing angle incidence X-ray diffraction, and piezoresponse force microscopy were performed. Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with a deposition rate of 1.1 Å/cycle have a more ideal hysteresis curve shape, higher remanent polarization (initial state: 16 μC/cm$^2$, wake up state: 22 μC/cm$^2$), and a higher orthorhombic phase portion than other deposition rates.

I. INTRODUCTION
Recently, several doped distorted fluorite structured HfO$_2$ ferroelectric materials have been extensively investigated. In particular, the admixture of 50 mol. % HfO$_2$-50 mol. % ZrO$_2$ solid-solution (Hf$_{0.5}$Zr$_{0.5}$O$_2$) has drawn a lot of interest for semiconductor memory applications, thanks to their high remanent polarization (P$_r$), wide tunability, and reliability. In general, it is accepted that the origin of the ferroelectricity of HfO$_2$-based thin films is the formation of the noncentrosymmetric orthorhombic phase (o-phase, space group Pca2$_1$). Even though the noncentrosymmetric o-phase is desirable for the ferroelectricity of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films, the o-phase is a thermodynamically unstable phase. Several recent theoretical and experimental studies demonstrated the origin of the ferroelectric o-phase and the influences of the various conditions such as film thickness, annealing temperature, process temperature, and doping cations on the formation and portion of the ferroelectric o-phase. 

Despite recent active studies, the focus of most studies on the emergence origin of the o-phase is tailored to subsequent processes. The films could have in situ crystallized nuclei of about 1 nm during atomic layer deposition (ALD), and the initial nuclei act as seeds to affect the final grain of more than 5 nm in size, which crystallizes during postmetallization annealing (PMA). Although previous studies have suggested that the o-phase is thermodynamically stabilized at a particular grain size, the effect of the initial nuclei on the as-deposited state of the grain size accompanying the ferroelectricity-induced crystal structure has been overlooked.

In this work, the influence of the deposition rate for the ferroelectric properties of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films from the viewpoint of the crystallographic structures and interface properties was carefully
examined. To perform quantitative analysis, deconvolution of glancing incidence X-ray diffraction (GIXRD) measurement in the 2 theta range of 25°–35° of Hf0.5Zr0.5O2 with various deposition rates was conducted by fitting to the superposition of Gaussian functions to determine the integrated peak areas and based on peak positions reported in previous studies.  

II. EXPERIMENTS

The 10 nm thick Hf0.5Zr0.5O2 films were deposited on an oxidized silicon substrate deposited with a 50 nm thick TiN metal electrode, using atomic layer deposition (ALD) at a process temperature of 300 °C. A single source of Tetrakis(ethylmethylamido)hafnium(IV) (TEMAHf) and Tetrakis(ethylmethylamido)zirconium (IV) (TEMAZr) was used as a hafnium-precursor and a zirconium-precursor, respectively. O2 (initial state: ~16 μC/cm2, wake up state: ~22 μC/cm2) than other deposition rates with the highest o-phase portion (0.48). Therefore, our research demonstrates that the grain size accompanying ferroelectricity can be controlled by the deposition rate with the initial nuclei at the as-deposited state by quantitatively analyzing the ferroelectric properties and corresponding crystallographic structures that depend on the film deposition rate. This new approach to controlling the grain size by controlling the deposition rate provides more opportunities to improve the performance of high-quality HfO2-based ferroelectric films.

III. RESULTS AND DISCUSSION

The deposition rate-dependent electrical properties are witnessed in Figs. 1(a) and 1(b), and a summary of the Pτ values of the Hf0.5Zr0.5O2 films with various deposition rates is depicted in Fig. 1(c). Generally, when a ferroelectric P-E curve is obtained, a triangular bipolar pulse is applied. Figure 1(a) shows the direct observation of the switching instantaneous current during a triangular bipolar pulse excitation, which is the change in charge with the change in time between each point, and the corresponding hysteresis curves are shown in Fig. 1(b). As shown in Fig. 1, Hf0.5Zr0.5O2 with a deposition rate of 1.1 Å/cycle has an ideal hysteresis curve with a high Pτ value of ~16 μC/cm2 and a switching current despite the initial state. Hf0.5Zr0.5O2 with a deposition rate of 0.9 Å/cycle has a slightly more tilt and the most distorted hysteresis curve (Pτ,initial value: ~9 μC/cm2), and the hysteresis curve of Hf0.5Zr0.5O2 with a deposition rate of 1.4 Å/cycle is the flattest (Pτ,initial value: ~5 μC/cm2).

To examine the variation of ferroelectric properties with electric field cycles (the wake-up state), hysteresis curves (left panel) and

![FIG. 1](image-url) (a) Switching instantaneous current during a triangular bipolar pulse excitation and (b) the corresponding hysteresis curves of the Hf0.5Zr0.5O2 films with various deposition rates. (c) The variation of remanent polarization (Pτ) values as a function of the deposition rate of the Hf0.5Zr0.5O2 films.
$\varepsilon_r$-E curves (right panel) were measured with an increase in the number of electric field cycles, as shown in Fig. 2. When the Hf$_{0.5}$Zr$_{0.5}$O$_2$ films are in the initial state, the hysteresis curve shapes were tilted with small humps, especially in the deposition rates of 0.9 and 1.4 Å/cycle. However, as the number of electric cycles increases, the shape of the hysteresis curves becomes more ideally shaped (square-like). The $\varepsilon_r$-E curves (right panel) show the butterfly-like shape, which is a typical ferroelectric characteristic. As the number of electric cycles increases, the dielectric constant values of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films approach 30. The variation in the dielectric constant value makes it easier to analyze the crystal structure than the shape of the hysteresis curve. The dielectric constant values of t-, o-, and m-phases are 17–20, ~30, and 35–40, respectively. As shown in the right panel of Fig. 2 and in Table I, the dielectric constant values of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with deposition rates of 0.9, 1.1, and 1.4 Å/cycle in the initial state are 34, 31.5, and 25, respectively. This means that the t-, o-, and m-phases are predominant at film deposition rates of Hf$_{0.5}$Zr$_{0.5}$O$_2$ of 0.9 Å/cycle, 1.1 Å/cycle, and 1.4 Å/cycle, respectively.

Hoffmann et al. reported that the oxygen vacancies (V$_O$) of Gd:HfO$_2$ decrease the free energy of the o-phase and t-phase by about 2.4 meV/V$_O$ concentration(%) and about 3.1 meV/V$_O$ concentration (%), respectively. Assuming that the V$_O$ effect is the same in Hf$_{0.5}$Zr$_{0.5}$O$_2$ if 10% of V$_O$ are present in Hf$_{0.5}$Zr$_{0.5}$O$_2$, the free energy of the t-phase is further reduced by 7meV and 31meV compared to the o-phase and m-phase, respectively. Therefore, the V$_O$ concentration in Hf$_{0.5}$Zr$_{0.5}$O$_2$ should be higher when the Hf$_{0.5}$Zr$_{0.5}$O$_2$ film is deposited with a higher deposition rate, and a higher t-phase portion is expected, which is inconsistent with the observed experimental result. Therefore, the ferroelectric properties of each deposition rate cannot be explained by the influence of oxygen vacancies alone. Thus, in order to understand the ferroelectric properties of each deposition rate, various approaches are required such as the viewpoint of crystallographic structures and the interface.

**FIG. 2.** Ferroelectric hysteresis (P-E) curves (left panel) and dielectric constant-electric field ($\varepsilon_r$-E) curves (right panel) of the Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with (a) 0.9 Å/cycle, (b) 1.1 Å/cycle, and (c) 1.4 Å/cycle.
characteristics. To evaluate the internal crystal structure compositions, the Hf$_{0.5}$Zr$_{0.5}$O$_2$ films were examined by GIXRD spectra measurements, with a 2 theta range of 25°–35°, as shown in Fig. 3. However, clear-cut identification of the t-, o-, and m-phases in an Hf$_{0.5}$Zr$_{0.5}$O$_2$ film is pretty challenging. Especially, the peak near 2 theta of 30.5° was designated as the combination of the o-phase (o111) and t-phase (011) due to their structural similarities. Some previous research studies reported t(011) peak positions for HfO$_2$ and ZrO$_2$ and o(111) peak position for Hf$_{0.5}$Zr$_{0.5}$O$_2$. Park et al. described that the peaks at 30.4° and 30.8° could be assigned as o(111) and t(011) peaks based on Vegard’s law. In addition, by using the Gaussian function, the diffraction peak could be deconvoluted by (m-111), (o111), (t011), and (m111) located at 28.54°, 30.4°, 30.8°, and 31.64°, as shown in Fig. 3. The relative ratio of each phase that is obtained by integrating the area of each Gaussian peak is summarized in Table I for the deposition rates of 0.9, 1.1, and 1.4 Å/cycle. The phase with the maximum relative ratio is the t-phase (0.47) in the Hf$_{0.5}$Zr$_{0.5}$O$_2$ film with 0.9 Å/cycle, o-phase (0.48) in the Hf$_{0.5}$Zr$_{0.5}$O$_2$ film with 1.1 Å/cycle, and m-phase (0.44) in the Hf$_{0.5}$Zr$_{0.5}$O$_2$ film with 1.4 Å/cycle. As can be easily understood from the quantitative parameters of Table I, the t-phase is predominant in the crystal structure of the Hf$_{0.5}$Zr$_{0.5}$O$_2$ film with 0.9 Å/cycle, o-phase is predominant in the crystal structure of the Hf$_{0.5}$Zr$_{0.5}$O$_2$ film with 1.1 Å/cycle, and m-phase is predominant in the crystal structure of the Hf$_{0.5}$Zr$_{0.5}$O$_2$ film with 1.4 Å/cycle. This result suggests that the deposition rate during Hf$_{0.5}$Zr$_{0.5}$O$_2$ film deposition primarily affects the crystal structure compositions. In addition, the dielectric constant values, relative ratio values, and their correlations for each of the phases obtained in our study are reasonable compared to both previous experimental and theoretical studies. Hoffmann et al. suggested a qualitative model for film crystallinity of doped-HfO$_2$, which depends on film thickness, dopant concentration, and thermal budget. According to this model, the thicker film leads to more m-phase and the thinner film leads to more t-phase. The o-phase exists somewhere at the boundary of the phase between t- and m-phases. Park et al. reported that the Hf$_{0.5}$Zr$_{0.5}$O$_2$ films become crystallized as the film thickness increases with the accompanying increase in grain size. The authors reported that a 5.5 nm Hf$_{0.5}$Zr$_{0.5}$O$_2$ film with a small grain size is crystallized mostly with the t-phase, and the crystallization occurs mostly with the o-phase when the film thickness reaches to 10 nm with a bigger grain size. Then, there is an increasing portion of the m-phase with the increasing film thickness so that the m-phase grows on top of the o-phase and t-phase. Materlik et al. suggested that the o-phase can be thermodynamically stabilized at the appropriate grain size because the surface energy and bulk free energy of the o-phase are between the t-phase and the m-phase.

Deposited state films could have in situ crystallized nuclei of about 1 nm in size during ALD, and the initial nuclei affect the final grain of more than 5 nm in size, which crystallizes during PMA. Therefore, the initial nuclei according to the deposition rate must be considered to control grain size. It can be deduced that the initial nuclei of low deposition rates lead to small grain sizes with the t-phase during crystallization, while the initial nuclei of high deposition rates lead to a large grain size with the m-phase during crystallization. The o-phase requires a proper grain size, the grain size can be controlled by the deposition rate, and 1.1 Å/cycle is the most suitable deposition rate.

In addition, the film thickness effect was observed in Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with various deposition rates, as shown in Fig. 4. HZO films exhibit the same trend under all deposition rate conditions, depending on the thickness effect: a 6 nm thick film with a small grain size has a distorted hysteresis curve dominated by the t-phase, a 10 nm thick film with a proper grain size has an ideal ferroelectric P–E curve dominated by the o-phase, and as the thickness increases to 13 nm with a large grain size, the m-phase portion increases and the remanent polarization has drastically reduced. This observation suggests that the effect of the deposition rate inducing the change in grain size discussed above is valid.

Functional switching properties of the Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with various deposition rates have been evaluated by piezoresponse force microscopy (PFM). The switching characteristics of the Hf$_{0.5}$Zr$_{0.5}$O$_2$...
FIG. 4. Ferroelectric hysteresis (P-E) curves of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with (a) 0.9 Å/cycle, (b) 1.1 Å/cycle, and (c) 1.4 Å/cycle with film thickness. The variation of remanent polarization (P$_r$) values of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with (d) 0.9 Å/cycle, (e) 1.1 Å/cycle, and (f) 1.4 Å/cycle as a function of film thickness.

films are demonstrated by the PFM amplitude and PFM phase loops [Figs. 5(a) and 5(b)]. The PFM amplitude and PFM phase loops obtained by sweeping DC bias represent a butterfly-like shape curve and an about 180° PFM phase switching, respectively. The slope of the PFM phase loops and the PFM amplitude shows the same tendency as the ferroelectric characteristics of the Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with various deposition rates mentioned above. The bidomain phase images in Fig. 5(c) were scanned by using an AC-biased PFM

FIG. 5. (a) PFM amplitude and (b) PFM phase loops of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with various deposition rates. (c) The bidomain phase images of Hf$_{0.5}$Zr$_{0.5}$O$_2$ films with various deposition rates.
The bidomain phase images present dark (−3 V) and bright (+3 V) contrast regions with the near 180° switching phase difference, which stands for the downward and upward polarization states, respectively.

Pulse switching current measurements were performed to evaluate the interfacial properties with ferroelectric switching kinetics. In this measurement, first, a polling pulse (10 μs) is applied in the opposite direction of the switching pulse, and then, a switching pulse (10 μs) is applied to measure the switching current with various magnitudes of the applied switching pulse.22,23

As shown in Figs. 6(a) and 6(b), the switching current was evaluated in both the positive (up to down) and negative (down to up) switching pulses. According to the polarization reversal theory, the switching current can be expressed as follows:

\[
I_{sw}(t) = I_{sw}^{0} e^{-\frac{t-t_{sw}}{R_{t}C_{i}}} (t_{0} < t < t_{sw}),
\]

where \(I_{0}\) is the starting time of ferroelectric switching, \(R_{t}\) is the total resistance of the measurement system, \(C_{i}\) is the interfacial capacitance, \(t_{sw}\) is the time at which the switching process is finished, and \(I_{sw}^{0}\) is the current when the switching process is started. According to the proposed model of Kim et al., the value of \(C_{i}\) includes the dead-layer capacitance of the interface and the nonferroelectric phase capacitance of the interface.23 As can be seen from the variation values of \(C_{i}\) in Fig. 6(c), the interface property of the Hf0.5Zr0.5O2 film with 1.1 Å/cycle is also the best.

IV. CONCLUSION

In this work, the influence of the deposition rate on Hf0.5Zr0.5O2 films was systematically examined from the viewpoint of the crystallographic structures and interface properties. It was shown that the Hf0.5Zr0.5O2 film with 0.9 Å/cycle has a distorted hysteresis curve (\(P_{r, \text{initial}} : -9 \mu \text{C/cm}^2\), \(\varepsilon_{r, \text{initial}} : 34\)), and t-phase with the highest relative ratio (0.47); the Hf0.5Zr0.5O2 film with 1.1 Å/cycle has an ideal hysteresis curve (\(P_{r, \text{initial}} : -16 \mu \text{C/cm}^2\), \(\varepsilon_{r, \text{initial}} : 31.5\)), and o-phase with the highest relative ratio (0.48); and the Hf0.5Zr0.5O2 film with 1.4 Å/cycle has a flat hysteresis curve (\(P_{r, \text{initial}} : -25 \mu \text{C/cm}^2\), \(\varepsilon_{r, \text{initial}} : 25\), and m-phase with the highest relative ratio (0.44). This experimental observation suggests that the grain size can be controlled by controlling the deposition rate, and the low deposition rate leads to a small grain size with the t-phase and the high deposition rate leads to a large grain size with the m-phase. Even though this is the first experimental evidence of the ferroelectric properties of Hf0.5Zr0.5O2 films with deposition rates, the material characterization is very limited to demonstrate the substantial property variation in Hf0.5Zr0.5O2 films with exact process parameters. Therefore, a systematic and extensive study (i.e., XPS, HRTEM, and in situ monitoring) is needed as future work from the viewpoint of material engineering. Nevertheless, this work also gives hints that Hf0.5Zr0.5O2 films with an appropriate grain size with the o-phase with high-quality ferroelectricity can be obtained from the initial film deposition stage by controlling the deposition rate.

ACKNOWLEDGMENTS

This work was supported in part by the Ministry of Trade, Industry and Energy, Korea, under Project Nos. 10067789 and 10067746, and in part by the Korea Semiconductor Research Consortium Support Program for the development of the future semiconductor device. This work was also supported by Grant Nos. NRF-2019M3F3A1A02071969 and NRF-2019M3F3A1A02071966.

REFERENCES

1. J. Mueller, U. Schroeder, T. S. Boescke, I. Mueller, U. Boettger, L. Wilde, J. Sundqvist, M. Lemberger, P. Kuecher, T. Mikolajick, and L. Frey, J. Appl. Phys. 110, 114113 (2011).
2. S. Mueller, C. Adelmann, A. Singh, S. Van Elshocht, U. Schroeder, and T. Mikolajick, ECS J. Solid State Sci. Technol. 1, N123–N126 (2012).
3. S. Mueller, J. Mueller, A. Singh, S. Riedel, J. Sundqvist, U. Schroeder, and T. Mikolajick, Adv. Funct. Mater. 22, 2412–2417 (2012).
4. T. Schenk, S. Mueller, U. Schroeder, R. Materlik, A. Kersch, M. Popovic, C. Adelmann, S. Van Elshocht, and T. Mikolajick, in Proceedings of the European Solid-State Device Research Conference (ESSDERC) (IEEE, 2013), pp. 260–263.
5. S. Starschich and U. Boettger, J. Mater. Chem. C 5, 333–338 (2017).
6. Y. S. Boscke, J. Muller, D. Brauhaus, U. Schroeder, and U. Boettger, Appl. Phys. Lett. 99, 102903 (2011).
7. S. V. Barabash, D. Pramanik, Y. Zhai, B. Magyari-Kope, and Y. Nishio, ECS Trans. 75, 107–121 (2017).
8. M. H. Park, H. J. Kim, Y. H. Lee, Y. J. Kim, T. Moon, K. D. Kim, S. D. Hyun, and C. S. Hwang, Nanoscale 8, 13898–13907 (2016).
9. E. D. Grimley, T. Schenk, T. Mikolajick, U. Schroeder, and J. M. LeBeau, Adv. Mater. Interfaces 5, 1701258 (2018).
10. Muller, T. S. Boscke, U. Schroder, S. Mueller, D. Brauhaus, U. Bottger, L. Frey, and T. Mikolajick, Nano Lett. 12, 4318–4323 (2012).
11. M. H. Park, H. J. Kim, Y. J. Kim, W. Lee, T. Moon, K. D. Kim, and C. S. Hwang, Appl. Phys. Lett. 105, 072902 (2014).
12. M. H. Park, H. J. Kim, Y. J. Kim, W. Jeon, T. Moon, and C. S. Hwang, Phys. Status Solidi RRL 8, 532–535 (2014).
13. M. Lee, Y.-T. Wei, K.-Y. Chu, J.-J. Huang, C.-W. Chen, C.-C. Cheng, M.-J. Chen, H.-Y. Lee, Y.-S. Chen, and L.-H. Lee, IEEE Electron Device Lett. 36, 294–296 (2015).
14. M. H. Park, Y. H. Lee, H. J. Kim, Y. J. Kim, T. Moon, K. D. Kim, J. Muller, A. Kersch, U. Schroeder, T. Mikolajick, and C. S. Hwang, Adv. Mater. 27, 1811–1831 (2015).
15. M. H. Park, H. J. Kim, Y. J. Kim, W. Lee, T. Moon, and C. S. Hwang, Appl. Phys. Lett. 102, 242905 (2013).
16. S. Oh, T. Kim, M. Kwak, J. Song, J. Woo, S. Jeon, I. K. Yoo, and H. Hwang, IEEE Electron Device Lett. 38, 732–735 (2017).
17. T. Kim, J. Park, B. H. Cheong, and S. Jeon, Appl. Phys. Lett. 112, 092906 (2018).
18. T. Kim and S. Jeon, IEEE Trans. Electron Devices 65, 1771–1773 (2018).
19. X. Sang, E. D. Grimley, T. Schenk, U. Schroder, and J. M. LeBeau, Appl. Phys. Lett. 106, 162905 (2015).
20. O. Ohtaka, H. Fukui, T. Kunisada, T. Fujisawa, K. Funakoshi, W. Utsumi, T. Irfuine, K. Kuroda, and T. Kikegawa, J. Am. Ceram. Soc. 84, 1369–1373 (2001).
21. O. Ohtaka, H. Fukui, T. Kunisada, T. Fujisawa, K. Funakoshi, W. Utsumi, T. Irfuine, K. Kuroda, and T. Kikegawa, Phys. Rev. B: Condens. Matter Mater. Phys. 63, 174108 (2001).
22. M. H. Park, Y. H. Lee, H. J. Kim, Y. J. Kim, T. Moon, K. D. Kim, S. D. Hyun, T. Mikolajick, U. Schroeder, and C. S. Hwang, Nanoscale 10, 716–725 (2018).
23. M. Hoffmann, U. Schroeder, T. Schenk, T. Shimizu, H. Funakubo, O. Sakata, D. Pohi, M. Drescher, C. Adelmann, R. Materlik, A. Kersch, and T. Mikolajick, J. Appl. Phys. 118, 072006 (2015).
24. D.-Y. Cho, H. S. Jung, I.-H. Yu, J. H. Yoon, H. K. Kim, S. Y. Lee, S. H. Jeon, S. W. Han, J. H. Kim, T. J. Park, B.-G. Park, and C. S. Hwang, Chem. Mater. 24, 3534–3543 (2012).
25. J. E. Jaffe, R. A. Bachorz, and M. Gutowski, Phys. Rev. B 72, 144107 (2005).
26. R. Materlik, C. Kunneth, and A. Kersch, J. Appl. Phys. 117, 134109 (2015).
27. H. J. Kim, M. J. Park, Y. J. Kim, Y. H. Lee, T. Moon, K. D. Kim, S. D. Hyun, and C. S. Hwang, Nanoscale 8, 1383 (2016).
28. M. H. Park, T. Schenk, C. M. Fancher, E. D. Grimley, C. Zhou, C. Richter, J. M. LeBeau, J. L. Jones, T. Mikolajick, and U. Schroeder, J. Mater. Chem. C 5, 4677–4690 (2017).