

HCl-based halide vapor phase epitaxy and selective-area HCl gas etching of (−112) β -Ga₂O₃

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ABSTRACT

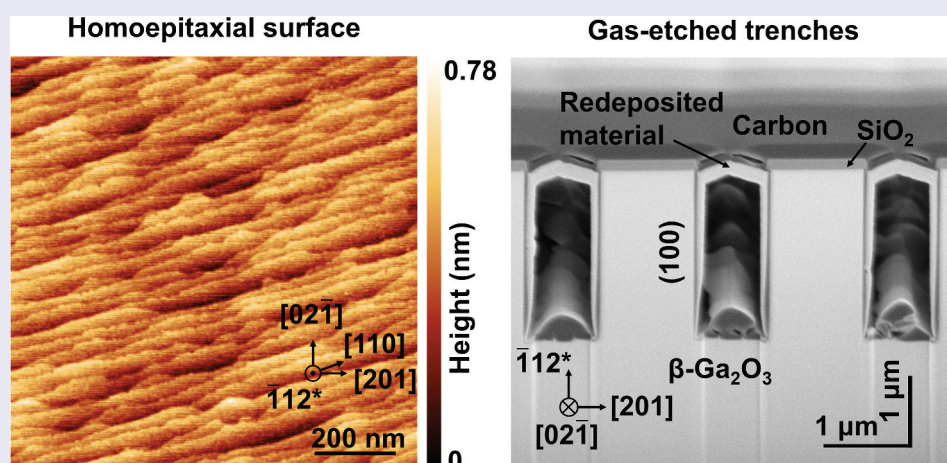
We propose (−112) and crystallographically equivalent (1−1−2), (−1−12), and (11−2) planes as the fundamental crystal orientations for β -Ga₂O₃ studies. These planes correspond to the {100} planes of the slightly distorted face-centered-cubic oxygen sublattice in β -Ga₂O₃ and therefore represent one of the primary crystallographic planes. On this basis, we have demonstrated both homoepitaxial growth and HCl gas etching on (−112) β -Ga₂O₃ substrates using an HCl-based halide vapor phase epitaxy system in order to clarify both the growth and etching characteristics on the (−112) plane. In homoepitaxy, the epilayer exhibited single crystallinity with tilt and twist dispersions comparable to those of the substrate and a step-and-terrace surface morphology with a root-mean-square roughness of 0.10–0.12 nm. Although slit-like pits whose sidewalls were vertically aligned (100) facets appeared on the surface, these pits were attributed to unintentional SiO₂ nanomasks at the interface and are expected to be eliminated by improving pre-growth surface treatments or the initial growth process. Furthermore, the concentration of Cl impurities in the epilayer was as low as $1 \times 10^{15} \text{ cm}^{-3}$, which was significantly lower than $2 \times 10^{16} \text{ cm}^{-3}$ observed in the simultaneously grown (001)-oriented homoepitaxial layer. For HCl gas etching, selective-area etching was performed using a SiO₂ mask with patterned windows. The etched structures clearly reflected the intrinsic crystal anisotropy. Side etching was minimized when the windows were aligned along the [02−1] direction due to the formation of exceptionally flat and vertical (100) facets, which possess the lowest surface energy density. Additionally, the vertical etch rate for the (−112) plane was approximately 50 times higher than the side etch rate for the (100) plane, enabling precise fabrication of high-aspect-ratio fins and trenches. These results—particularly the excellent surface smoothness achieved in homoepitaxy and the high-aspect-ratio patterning enabled by HCl-gas etching—demonstrate that the (−112) orientations are promising candidates for β -Ga₂O₃ studies.

ARTICLE HISTORY

Received 9 March 2026
Revised 10 May 2026
Accepted 25 May 2026

KEYWORDS

β -Ga₂O₃; (−112);
homoepitaxy; gas etching



IMPACT STATEMENT

We demonstrate HCl-based halide vapor phase epitaxy and selective-area HCl gas etching on (−112)-oriented β -Ga₂O₃, enabling twin-free atomically flat homoepitaxy and high anisotropic etching with flat, vertical (100) sidewalls.

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Introduction

β -Ga₂O₃ semiconductor

β -Ga₂O₃ has recently emerged as a promising ultra-wide-bandgap oxide semiconductor for next-generation power electronics applications [1]. This material offers compelling advantages over conventional non-oxide power semiconductors such as GaN, SiC, and diamond, including: (i) an exceptionally wide bandgap (≥ 4.43 eV) [2], which is among the largest for thermally stable binary metal oxides, enabling a high critical electric field of ~ 8 MV cm⁻¹ [3]; (ii) high-speed, scalable bulk single crystal growth capabilities through established melt-growth techniques including floating zone [4], Czochralski [5], edge-defined film-fed growth [6], vertical Bridgman [7,8], and oxide crystal growth from cold crucible [9], with demonstrated wafer sizes up to 6 inches [1,8]; (iii) compatibility with diverse epitaxial growth techniques such as halide vapor phase epitaxy (HVPE) [10–16], metal-organic chemical vapor deposition (MOCVD) [17,18], mist chemical vapor deposition [19], molecular beam epitaxy [20–23], and pulsed laser deposition [24]; (iv) established bandgap engineering through alloying with Al₂O₃, Sc₂O₃, and In₂O₃ [25–30]; (v) potential for achieving high-quality metal-oxide-semiconductor (MOS) interfaces with low interface state densities due to SiO₂/ β -Ga₂O₃ heterointerfaces that can endure high temperature annealing [31–33]; and (vi) compatibility with ion implantation doping [34,35] and ion cutting techniques [36], facilitated by effective crystal lattice recovery through post-implantation thermal annealing. These features make β -Ga₂O₃ a highly attractive candidate for high-power, high-frequency electronic devices [1].

From a manufacturing perspective, high growth rate epitaxy is essential for realizing thick drift layers required for the most promising vertical power device applications, and HVPE is widely regarded as a promising technique for this purpose. However, achieving device-grade homoepitaxial layers requires not only a high growth rate but also high crystalline quality, low unintentional impurity incorporation, and smooth surface morphology compatible with subsequent device processing. In monoclinic β -Ga₂O₃, these properties are strongly orientation dependent; substrate orientation influences growth kinetics and defect manifestation and can lead to surface roughening [12] and twin formation [37,38]. Therefore, the exploration of substrate orientation remains a key issue for establishing a reliable β -Ga₂O₃ platform for high-voltage power devices.

Exploring substrate orientations

To date, the research and development of β -Ga₂O₃-based vertical power devices have primarily relied on (001)-oriented substrates because the high HVPE

growth rate on this orientation is well suited for preparing thick drift layers capable of sustaining high voltages for vertical power-electronic applications [10–14]. However, the surface morphology of the (001) epilayers is often rough due to the formation of groove-like pits associated with dislocations [12], which necessitates subsequent chemical mechanical polishing (CMP) to planarize the surface for device fabrication [39,40]. This post-epitaxy CMP increases manufacturing cost and is therefore preferably avoided. In this context, substrates with other orientations, which can yield smoother epitaxial surfaces, have attracted increasing attention.

The (100) orientation is a promising option for obtaining smooth epitaxial surfaces. Atomically flat epitaxial surfaces with well-defined step and terrace structures can be obtained owing to the lowest surface energy density of the (100) plane [20,41]. However, to suppress twin formation arising from double positioning of adatoms on the (100) surface, the substrate must be miscut by at least 6° from the (100) surface normal [37].

The (011) orientation is another attractive candidate for achieving flat epitaxial surfaces. Recently, Goto et al. demonstrated with Cl₂-based HVPE (i.e. HVPE in which GaCl_x is produced by the reaction between Ga and Cl₂) that the groove-like pits observed on (001) epilayers can be eliminated on (011)-oriented substrates, likely because the relevant dislocations lie parallel to the (011) plane [12]. Similar smooth (011) surfaces have been reported for HCl-based HVPE (i.e. HVPE in which GaCl_x is produced by the reaction between Ga and HCl) [15] and MOCVD [42]. However, the epitaxial surface was not atomically flat due to step bunching [15], suggesting that optimization of the off-angle optimization is required.

Thus, exploration of substrate orientations remains an open research area, and we introduce an oxygen-sublattice-based perspective to propose new crystal orientations. Although β -Ga₂O₃ crystallizes in a complex monoclinic structure, the fundamental framework is governed by a slightly distorted face-centered-cubic (fcc) oxygen sublattice, which allows a pseudo-cubic representation of the crystal structure and facilitates the exploration of substrate orientations [43]. Here, the lattice vectors of the non-primitive fcc-based unit cell are $\mathbf{a}_{\text{fcc}} = \mathbf{b} + 1/2 \mathbf{c}$, $\mathbf{b}_{\text{fcc}} = -\mathbf{b} + 1/2 \mathbf{c}$, and $\mathbf{c}_{\text{fcc}} = 1/3 \mathbf{a} + 1/6 \mathbf{c}$, which gives lattice parameters of $a_{\text{fcc}} = b_{\text{fcc}} = 4.20$ Å, $c_{\text{fcc}} = 3.95$ Å, $\alpha_{\text{fcc}} = \beta_{\text{fcc}} = 90.1^\circ$, and $\gamma_{\text{fcc}} = 92.7^\circ$. In this fcc unit cell, the primary planes are $\{100\}_{\text{fcc}}$, $\{110\}_{\text{fcc}}$, and $\{111\}_{\text{fcc}}$, which correspond to $\{100\}$ and $\{\bar{1}12\}$; $\{010\}$, $\{\bar{1}02\}$, $\{512\}$, and $\{\bar{7}12\}$; and $\{201\}$, $\{101\}$, and $\{310\}$ of the monoclinic unit cell [43]. Among these oxygen-sublattice-derived major planes, we chose $(\bar{1}12)$ -or crystallographically equivalent $(1\bar{1}2)$,

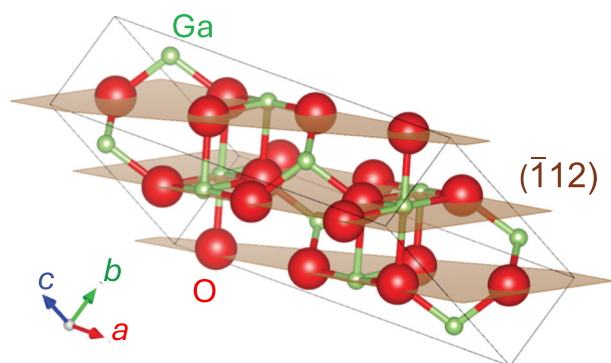


Figure 1. Unit cell of $\beta\text{-Ga}_2\text{O}_3$ showing the position of the $(\bar{1}12)$ plane. The spacing between adjacent planes is 0.21 nm.

$(\bar{1}12)$, or $(11\bar{2})$ planes—as a candidate orientation (see Figure 1 for the location of the $(\bar{1}12)$ plane). One reason is that the $(\bar{1}12)$ and (100) planes belong to the same $\{100\}_{\text{fcc}}$ family [43], suggesting step-and-terrace epitaxial surfaces. Another reason is that the $(\bar{1}12)$ plane is the closest to the (011) plane, with an interplanar angle of 19.7° , and is expected to yield groove-like-pit-free epitaxial surfaces.

The $(\bar{1}12)$ orientation is also attractive from the viewpoint of crystallographic gas etching. We previously investigated HCl-gas etching on the most gas-etch-resistant (100) -oriented substrates and found that in-plane lateral etching was most pronounced along the direction perpendicular to the $\{\bar{1}12\}$ planes [44]. This result indicates that the $(\bar{1}12)$ -oriented substrates may enable the fastest vertical etching, potentially allowing the formation of extremely high-aspect-ratio trenches and fins with vertically aligned (100) -faceted sidewalls.

Therefore, in this study, we performed both homoepitaxial growth and gas etching on $(\bar{1}12)$ $\beta\text{-Ga}_2\text{O}_3$ substrates to evaluate the potential of this orientation.

HVPE on $(\bar{1}12)$ $\beta\text{-Ga}_2\text{O}_3$

Experimental methods

Homoepitaxy was performed on $(\bar{1}12)$ and (001) $\beta\text{-Ga}_2\text{O}_3$ substrates using a custom-made HCl-based HVPE system that has been employed in our previous homoepitaxy experiments on (001) , $(\bar{1}02)$, and (011) -oriented $\beta\text{-Ga}_2\text{O}_3$ substrates [15,16]. This system is equipped with a horizontal quartz reactor that is divided into an upstream source zone and a downstream growth zone. A GaCl precursor was synthesized in the source zone at 610°C via the reaction between Ga metal ($>99.9999\%$ pure) and HCl gas ($>99.999\%$ pure). Under these conditions, the supplied HCl gas was completely consumed, generating an equimolar amount of GaCl gas. Homoepitaxy was carried out by introducing GaCl and O_2 ($>99.99995\%$

pure) precursors, together with additional HCl gas to suppress parasitic reactions [45], onto the $(\bar{1}12)$ and (001) $\beta\text{-Ga}_2\text{O}_3$ substrates mounted on a rotating holder in the growth zone heated at 1030°C . The reactive gases were carried by purified N_2 gas (dew point $< -110^\circ\text{C}$) under atmospheric pressure (approximately 100 kPa), and the total gas flow rate through the reactor was maintained at 8 slm. The partial pressures of GaCl, O_2 , and HCl were set at 0.125, 1.25, and 0.188 kPa, respectively. The growth time was 15 min.

The resulting epilayer was characterized using various methods. The epitaxial structure was examined using X-ray diffraction (XRD) measurements using $\text{Cu K}\alpha_1$ radiation. The surface morphology was observed using differential interference contrast (DIC) optical microscopy, atomic force microscopy (AFM), and scanning electron microscopy (SEM). Cross-sectional observation was also performed using focused ion beam-SEM (FIB-SEM), scanning transmission electron microscopy (STEM) for high resolution energy-dispersive X-ray spectroscopy (EDS). The epilayer thickness and impurity concentrations of possible dopants (Si, Cl, N, and H) were measured by secondary ion mass spectrometry (SIMS) and the SIMS results were compared with those of the epilayer on the (001) substrate.

Results and discussion

The growth rate on the $(\bar{1}12)$ substrate was approximately half of that on the (001) substrate. The grown layer thickness and growth rate were $2.8\ \mu\text{m}$ and $11\ \mu\text{m h}^{-1}$ for the $(\bar{1}12)$ orientation, and $6.1\ \mu\text{m}$ and $24\ \mu\text{m h}^{-1}$ for the (001) orientation, respectively. The ratio of the growth rate on $(\bar{1}12)$ to that on (001) was 0.46, which is slightly lower than the previously reported growth-rate ratio of 0.6 for $(011)/(001)$ in our previous study [15]. One possible reason for the lower growth rate on the $(\bar{1}12)$ substrate than that on the (001) substrate is the lower surface energy density of the $(\bar{1}12)$ plane, $62.4\ \text{meV \AA}^{-2}$, compared with that of the (001) plane, $87.9\ \text{meV \AA}^{-2}$ [46]. The lower surface energy density of the $(\bar{1}12)$ plane suggests that this surface is relatively stable, with a lower density of dangling bonds or reactive bonding sites, thereby decreasing the incorporation probability of adatoms on the surface and resulting in a lower growth rate. For the (011) plane, we could not find literature reporting its surface energy density. However, the surface energy density of the (011) plane is expected to be higher than that of the $(\bar{1}12)$ plane because the (011) plane is slightly inclined by 19.73° from the $(\bar{1}12)$ plane that belongs to the $\{100\}_{\text{fcc}}$ oxygen-sublattice plane, which likely results in a higher dangling-bond density. Therefore, it is also reasonable that

the growth rate on the ($\bar{1}12$) plane is slightly lower than that on the (011) plane.

The ($\bar{1}12$) epitaxial layer exhibited single crystallinity, with tilt and twist dispersions comparable to those of the substrate. Figure 2 shows XRD patterns for the epitaxial wafer (epiwafer) and the corresponding substrate. In the θ - 2θ patterns, only the $\bar{1}12$ diffraction peaks from the epiwafer were observed within the measured scan range at the same angles from the substrate (Figure 2(a)), indicating a single out-of-plane orientation without lattice strain in the layer. Note that the weak but sharp peak on the lower-angle shoulder of the main peak of the epiwafer originates from an impurity X-ray line other than Cu $K\alpha_1$, and it also appeared in the substrate scan. In the skew-symmetric ϕ scan patterns, a strong 020 peak was observed for both the epiwafer and the substrate (Figure 2(b)), indicating the absence of rotation domains in the epilayer. The 020 peak was also accompanied by a weak but sharp shoulder peak in both scan patterns, which should be originated from the 021 diffraction because its reciprocal-lattice point lies close to that of 020. It should be noted that twin-free homoepitaxy was achieved on the ($\bar{1}12$) plane although both ($\bar{1}12$) and (100) planes belong to the same $\{100\}_{\text{fcc}}$ family of the oxygen sublattice of β -Ga₂O₃, as described earlier. Figure 2(c) presents normalized ω -rocking curves of the $\bar{1}12$ and 020 peaks for both the epiwafer and the substrate. The full widths at half maximum (FWHMs) of the $\bar{1}12$ peak were 66 arcsec (epiwafer) and 55 arcsec (substrate), whereas those of 020 peak were 47 arcsec (epiwafer) and 42 arcsec (substrate), indicating that the epilayer maintains nearly the same tilt and twist spreads as the substrate and thus largely preserves the substrate crystalline quality.

The surface morphology of the ($\bar{1}12$) layer was very smooth overall, but some pits were present. Figure 3 shows a DIC optical micrograph of the homoepitaxial surface. Although groove-like pits reported for the (001) surface were not observed, numerous linear pits elongated along the $[02\bar{1}]$ direction were present, and the density of the pits was about $2 \times 10^5 \text{ cm}^{-2}$. Notably, these pits had a nearly uniform length of approximately 5 μm , suggesting that they originated from the same depth. In contrast, the regions outside the pits were extremely flat and appeared featureless under optical microscopy.

The surface morphology of the flat region was further investigated by AFM, as shown in Figure 4. The surface was revealed to consist of stairs-like step-and-terrace structures, providing an ideal surface for various applications. Considering the monolayer height of 0.21 nm (Figure 1), the steps were composed of monolayer- and bilayer-height steps, which correspond to dark and darker contrasts in the images. The root-mean-square

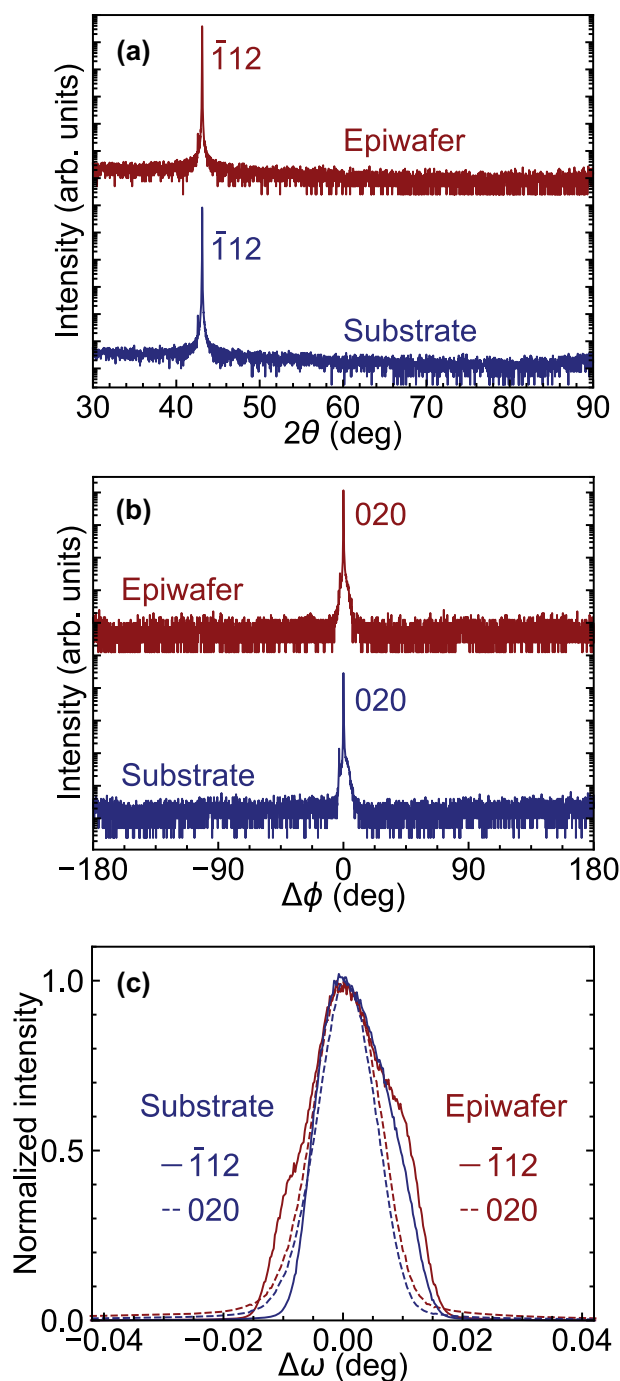


Figure 2. Summary of X-ray diffraction measurements of the ($\bar{1}12$) epiwafer and the corresponding substrate using Cu $K\alpha_1$ radiation. (a) θ - 2θ scan patterns for the $\bar{1}12$ diffraction. (b) Skew-symmetric ϕ scan patterns for the 020 diffraction. (c) ω -rocking curves of the observed $\bar{1}12$ and 020 diffraction peaks.

(RMS) roughness values for 5 $\mu\text{m} \times 5 \mu\text{m}$ and 1 $\mu\text{m} \times 1 \mu\text{m}$ scan areas were 0.12 and 0.10 nm, respectively. These RMS values are among the lowest reported for homoepitaxial β -Ga₂O₃ surfaces across various substrate orientations and growth techniques [42]. Notably, such a flat epitaxial surface on the ($\bar{1}12$) plane does not require a post-growth CMP process and is readily applicable to device fabrication. This represents a significant advantage over (001) epilayers, for which post-growth CMP is

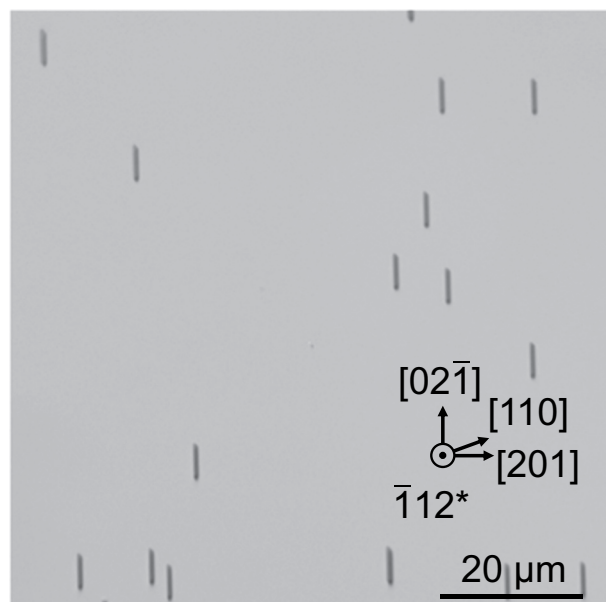


Figure 3. (a) Differential interference contrast optical microscopy image of the surface of the $(\bar{1}12)$ epilayer.

required to remove approximately half of the layer thickness [40], even when the lower growth rate of the $(\bar{1}12)$ plane relative to the (001) plane is taken into account.

On the other hand, in order to examine the origin of the linear pits, they were investigated from multiple viewing directions using SEM, as shown in Figure 5. Figure 5(a–c) correspond to a top view, a 54° -tilted cross-sectional view along $[0\bar{2}1]$, and a 54° -tilted cross-sectional view along $[201]$, respectively. Note that the FIB vertical cross-sectioning in Figure 5(b,c) was performed in planes perpendicular and parallel to the $[0\bar{2}1]$ -elongated linear pits, which means that the cross sections were perpendicular and parallel to the (100) plane, respectively. From these images, the linear pit was revealed to be a thin slit sandwiched between vertically aligned (100) facets and to have an isosceles triangular cross-sectional profile with a right-angled vertex pointing downward. Although we could not unambiguously identify the crystallographic planes forming the two equal-length sides of the isosceles triangular profile due to the very small slit width, they are facets parallel to the $[001]$ and $[010]$ directions. This inverted triangular shape indicates that the slit originated at the vertex and grew upward along the (100) facets, with its sides propagating along the $[001]$ and $[010]$ directions. The vertex depth was $2.6\text{ }\mu\text{m}$, which closely agrees with the $2.8\text{-}\mu\text{m}$ thickness measured by SIMS. This agreement indicates that the pits originated at the layer/substrate interface, which likely explains why the observed linear pits on the surface have the same length. It should be noted that such (100)-defined slit-like pits were also found in homo-epitaxial layers grown on (011) $\beta\text{-Ga}_2\text{O}_3$ substrates using the same HVPE system [15], though the pits were tilted with respect to the surface normal.

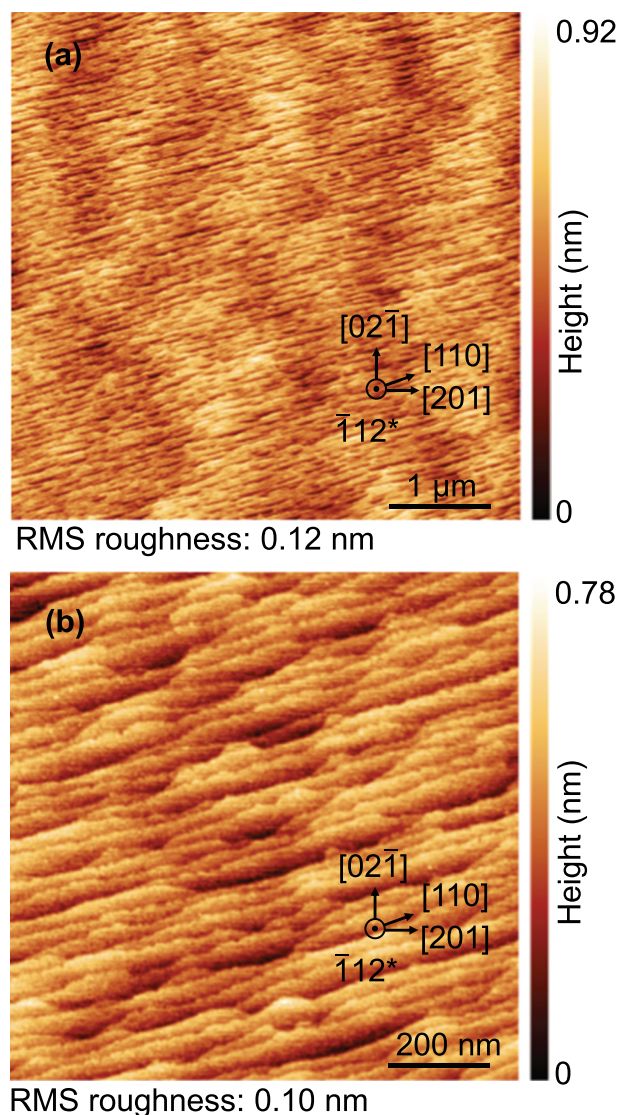


Figure 4. Atomic force microscopy images of a flat surface region of the $(\bar{1}12)$ epilayer with scan areas of (a) $5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$ and (b) $1\text{ }\mu\text{m} \times 1\text{ }\mu\text{m}$.

To identify the origin of the pit formation, cross-sectional STEM-EDS was performed in the vicinity of the vertex of the pit at the interface, as shown in Figure 6. Figure 6(a) shows a high-angle annular dark field (HAADF) STEM image, and Figure 6(b–e) show EDS maps of Ga, O, Si, and C for the corresponding scan area, respectively. Note that the TEM support mesh contains Si; therefore, the background Si signal is slightly higher than that of the other elements. The reduced Ga and O signals and the enhanced C signal in the pit region are consistent with the absence of $\beta\text{-Ga}_2\text{O}_3$ and the presence of a C deposit, used as a protective layer for FIB milling, respectively. In contrast, the enhanced Si signal at the pit vertex suggests the presence of unintentional SiO_2 nanostructures, which likely originate from quartz parts in the reactor, such as the quartz substrate holder and quartz tube. Because SiO_2 can act as a mask for selective-area growth for $\beta\text{-Ga}_2\text{O}_3$ [47], its presence at the interface reasonably accounts for the initiation of pit

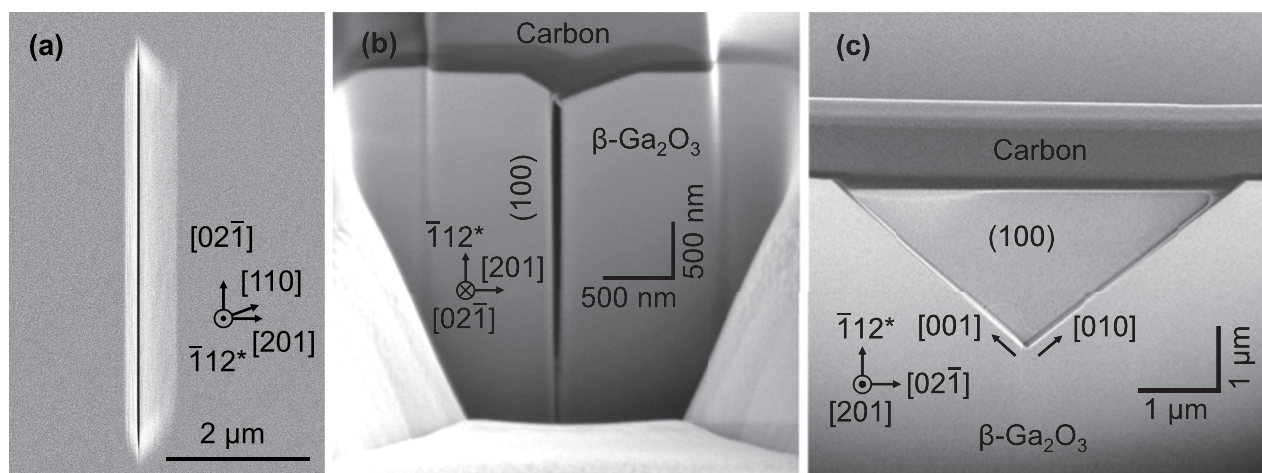


Figure 5. (Two columns) (a) Plan-view and (b) and (c) 54°-tilted cross-sectional scanning electron microscopy images of a slit-like pit observed on the $(\bar{1}12)$ epilayer. The exposed cross sections were perpendicular to the $[02\bar{1}]$ direction in (b) and parallel to the $[02\bar{1}]$ direction in (c).

formation. Other masking species may also contribute, such as CMP-induced surface defects or deposited $\beta\text{-Ga}_2\text{O}_3$ particles generated during the initial stage of growth. In any case, these pits are not intrinsic to the $(\bar{1}12)$ orientation but are related to the substrate surface condition and/or the early growth process, and thus should be mitigated by improving pre-growth surface treatments and optimizing the initial growth conditions.

Finally, the impurity concentrations in the $(\bar{1}12)$ and (001) layers were compared. Figure 7(a,b) show depth profiles of atomic concentrations of unintentionally doped Si, Cl, N, and H in the homoepitaxial layers grown on the $(\bar{1}12)$ and (001) substrates, respectively. Here, we particularly focus on Si and

Cl as they are major donor impurities in HCl-based HVPE. The Si concentrations were comparable, with values of $2 \times 10^{16} \text{ cm}^{-3}$ and $1 \times 10^{16} \text{ cm}^{-3}$ in the $(\bar{1}12)$ and (001) layers, respectively. The incorporation of Si is attributable to the environment in the growth zone, where the hydrogen and quartz components coexist [48], because reactive hydrogen slightly etches the quartz. However, this etching reaction can be prevented by replacing quartz components with quartz-free alternatives. On the other hand, the incorporation of Cl cannot be avoided as long as GaCl_x species are used as precursors and is therefore inevitable in HVPE. Nevertheless, the Cl concentration of the $(\bar{1}12)$ layer was as small as $1 \times 10^{15} \text{ cm}^{-3}$, which was significantly lower than that of

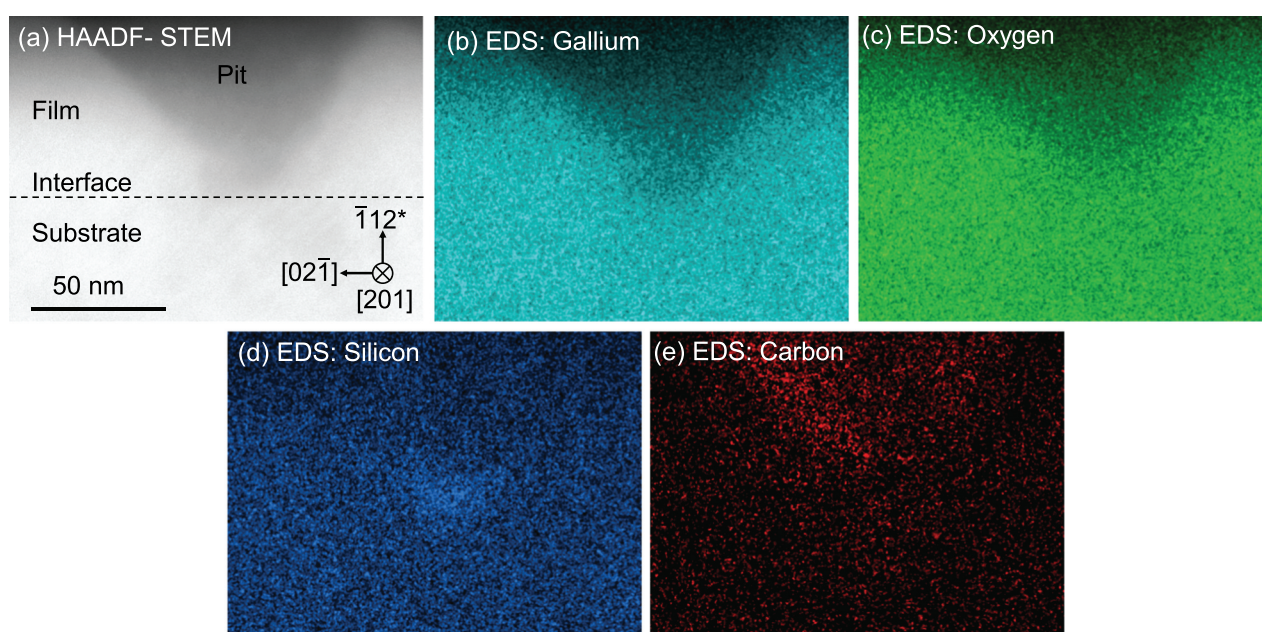


Figure 6. (Two columns) (a) Cross-sectional high-angle annular dark field scanning transmission electron microscopy (HAADF-STEM) image and (b)–(e) energy-dispersive X-ray spectroscopy (EDS) elemental maps of Ga, O, Si, and C, respectively, in the vicinity of the pit-generation region.

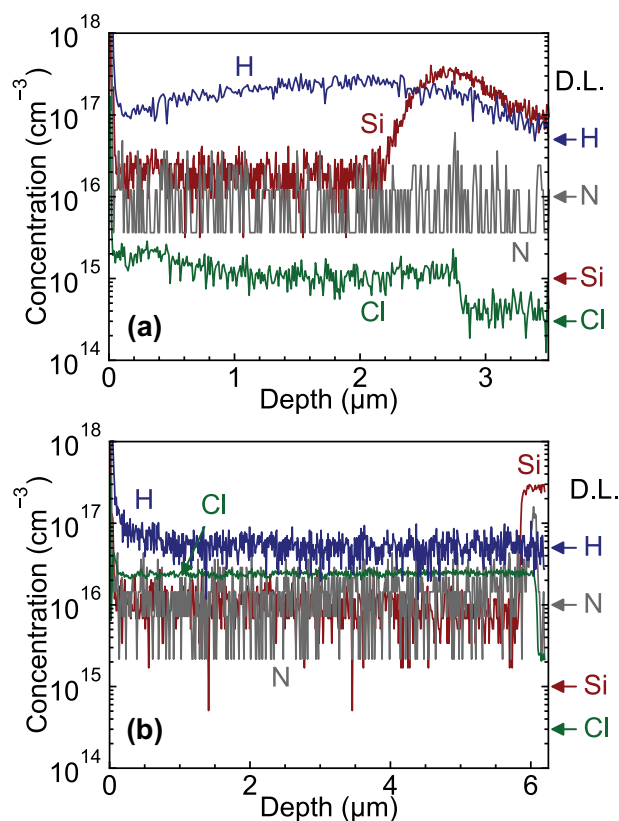


Figure 7. Depth profile of impurities in (a) the $(\bar{1}12)$ and (b) the (001) epilayers obtained by secondary ion mass spectroscopy. Arrows indicate detection limits.

the (001) layer ($2 \times 10^{16} \text{ cm}^{-3}$). This non-negligible orientation dependence of Cl incorporation is likely related to differences in surface bonding configurations between these two crystal planes, although the mechanism remains to be clarified in the future work. The difference in growth rate may also affect Cl incorporation because Cl could be incorporated into the growing layer before sufficient desorption occurs at the grown surface. In our previous experiments, a (001) homoepitaxial layer grown at a lower growth rate of $8.4 \mu\text{m h}^{-1}$ still showed a relatively high Cl concentration of $4.1 \times 10^{15} \text{ cm}^{-3}$. Although further systematic studies are required to separate the effects of growth rate and surface orientation, this result suggests that the pronounced reduction in Cl concentration for the $(\bar{1}12)$ layer cannot be explained by the growth rate alone and is likely associated with the crystallographic orientation of the growth surface. It should be noted that Si concentrations were comparable between the $(\bar{1}12)$ and (001) orientations, whereas Cl concentrations were significantly different. One possible explanation is that Si and Cl are incorporated into different lattice sites, namely Ga and O sites, respectively, and are therefore affected by different bonding states even for the same substrate orientation. In addition, Si may be more readily incorporated into the lattice than Cl because the Si–O bond is stronger than the

Cl–Ga bond. This difference in bonding strength could result in weaker and stronger orientation dependence for Si and Cl incorporation, respectively. The Cl concentration of the $(\bar{1}12)$ plane, in the low 10^{15} cm^{-3} range, was sufficiently small, given that the doping control required for vertical power devices is typically in the low 10^{16} cm^{-3} range. Therefore, the $(\bar{1}12)$ substrate is attractive not only for its excellent epitaxial surface morphology but also for its sufficiently low Cl incorporation.

HCl-gas etching on $(\bar{1}12)$ $\beta\text{-Ga}_2\text{O}_3$

Experimental methods

Prior to the etching process, a SiO_2 mask with etching windows was fabricated on a $(\bar{1}12)$ substrate by plasma-enhanced CVD using tetraethyl orthosilicate and O_2 precursors, followed by laser lithography and capacitively coupled plasma reactive-ion etching with a CHF_3/N_2 gas mixture. To investigate the HCl gas etching behavior, wagon-wheel and stripe-shaped windows were employed. The wagon-wheel pattern consists of 72 linear windows arranged at 5° intervals, starting from the $[201]$ direction, which is perpendicular to (100) . The length and width of each window were 50 and $0.7 \mu\text{m}$, respectively. The stripe pattern consists of linear windows aligned along the $[02\bar{1}]$ direction, which is parallel to (100) . The window and mask widths were 0.8 and $1.2 \mu\text{m}$, respectively.

Selective-area HCl-gas etching was performed on the SiO_2 -masked $(\bar{1}12)$ substrate in the same HVPE system that has also been employed in our previous gas etching experiments on (100) , (010) , (001) , $(\bar{1}02)$, and (011) -oriented $\beta\text{-Ga}_2\text{O}_3$ substrates [44,49–55]. Etching was carried out by supplying HCl gas to the substrate in the growth zone (used here as the etching zone) heated to 1038°C . The HCl gas was carried by N_2 gas under atmospheric pressure, while the total gas flow rate was kept at 8 slm. The HCl partial pressure was 62.5 Pa. The etching time was 10 min.

The resulting etched structures were examined using SEM and FIB–SEM.

Results and discussion

Anisotropy of in-plane side etching was first examined by measuring the side-etch rates of the wagon-wheel-patterned etched trenches, as shown in Figure 8. The measured side-etch rates from the top-view SEM image (Figure 8(a)) were summarized in a polar plot (Figure 8(b)). Note that the side-etch rate was calculated from the side-etch length of the trenches, defined as the spacing between the etching front and the mask edge, which could be measured by SEM observation from the surface normal at an acceleration voltage (V_{acc}) of 10 kV [50]. The side etching was remarkably

suppressed for the $[02\bar{1}]$ -oriented trenches; that is, side etching along the $[201]$ and $[\bar{2}0\bar{1}]$ directions was minimized, suggesting the development of high etch-resistant (100) sidewall facets with the lowest surface energy density [41]. In addition, the shape of the polar plot for the $(\bar{1}12)$ substrate exhibited an approximate twofold in-plane rotational symmetry, which is very similar to that for the (011) substrate [55]. The similarity likely reflects the close crystallographic relationship between the $(\bar{1}12)$ and (011) planes, as described earlier.

Then, a trench array aligned along the $[02\bar{1}]$ direction, which exhibited the minimum lateral etching, was observed using SEM, as shown in Figure 9. Figure 9(a–c) show SEM images near the trench ends, acquired in plan-view and tilted-view geometries with the tilt axis oriented along two different in-plane directions, respectively. Note that these images were taken at V_{acc} of 10 kV to clearly reveal the etching

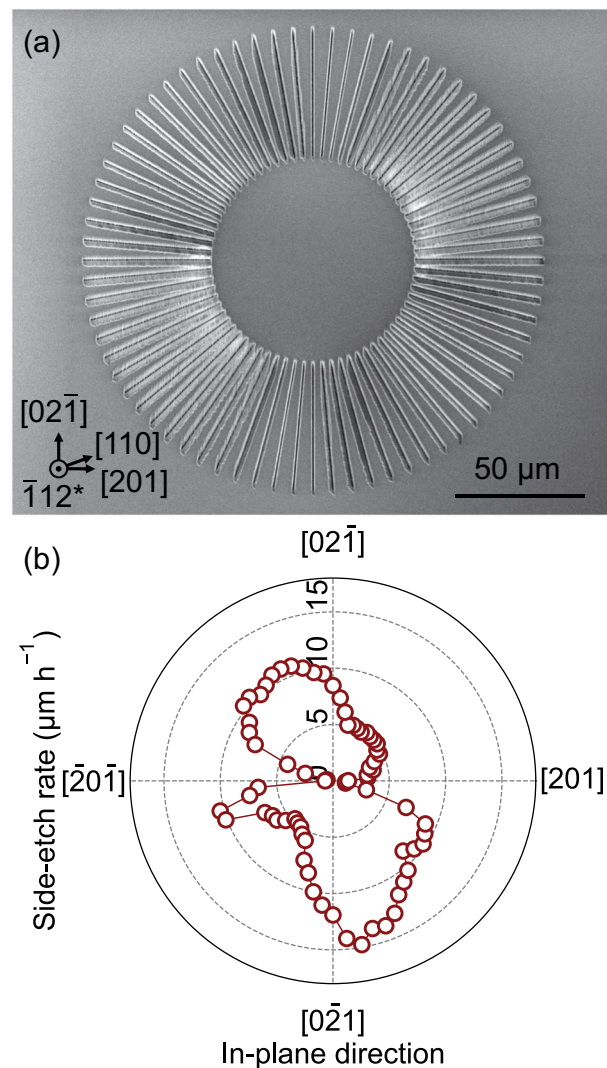


Figure 8. Summary of side-etching characterization for trenches etched beneath the wagon-wheel window pattern on the $(\bar{1}12)$ substrate. (a) Plan-view scanning electron microscopy image. (b) Polar plot of the side-etch rates extracted from the trenches shown in (a).

fronts. Figure 9(d) shows a cross-sectional tilted-view SEM image of the corresponding trenches near the center of the array; the cross section was taken

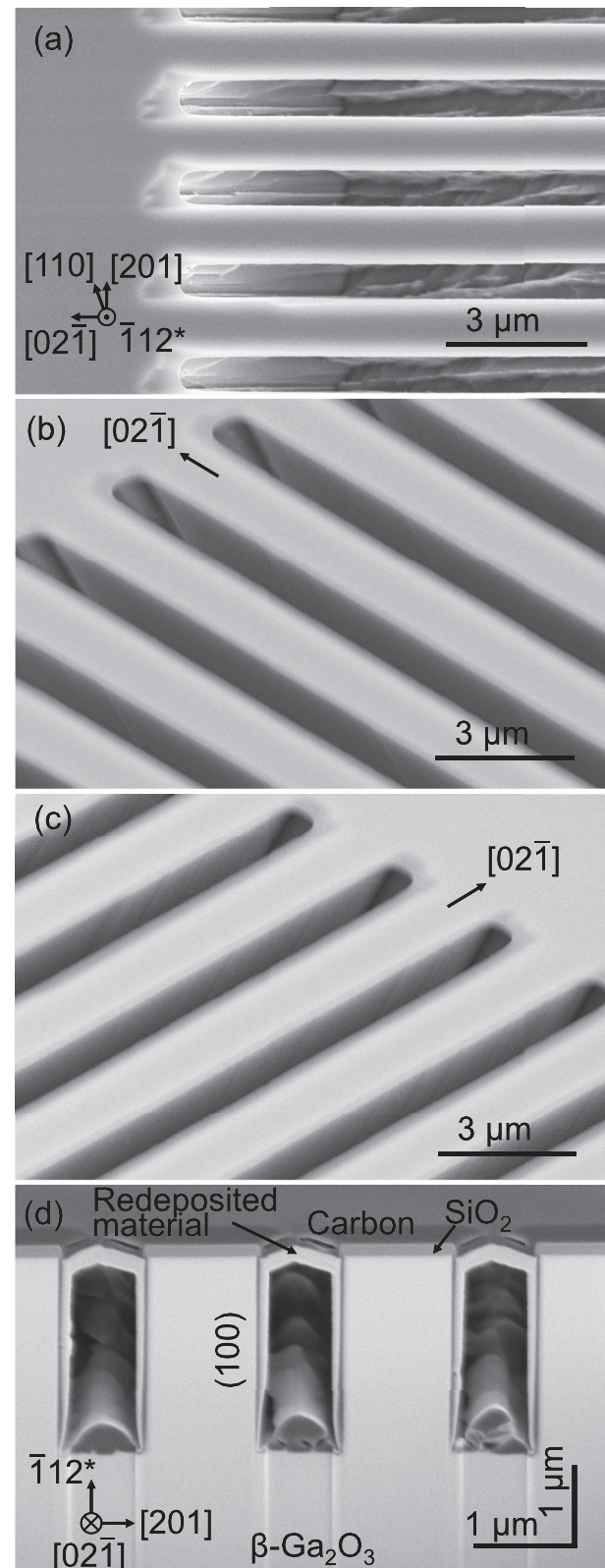


Figure 9. Summary of scanning electron microscopy observations of the trench array aligned along the $[02\bar{1}]$ direction on the $(\bar{1}12)$ substrate. (a) Plan-view image. (b) and (c) 54°-tilted-view images taken from different in-plane directions. (d) 54°-tilted-view image of the cross-section perpendicular to the $[02\bar{1}]$ direction.

perpendicular to the trenches, i.e. along the (100) plane. In this case, V_{acc} was set to 2 kV to enhance material contrast. These images collectively revealed that the trench profiles consisted of vertical, extremely flat (100)-faceted sidewalls and a relatively rough ($\bar{1}12$) bottom surface. The side-etch length and height of the (100) sidewalls were 0.04–0.05 and 2.43–2.48 μm , respectively, yielding a vertical-to-lateral etch-rate ratio of 47–55. This aspect ratio regarding the (100) sidewalls is higher than those of HCl-gas-etched vertical trenches on (010) substrates (11–14) [49] and ($\bar{1}02$) substrates (7.9–11.2) [54] formed under the same etching conditions, representing the highest value among the major oxygen-sublattice-derived substrate orientations that enable vertical trench formation [43]. This high anisotropy also enables precise etching that faithfully reproduces the mask pattern. Although the bottom surface roughness may be a concern, it is known to be mitigated by lowering the etching temperature [53,56]. Furthermore, unlike conventional plasma-based dry etching, gas-phase etching such as HCl-gas etching introduces no plasma-induced damage to the processed surfaces and is therefore well suited for device applications. Therefore, the ($\bar{1}12$) orientation is particularly beneficial as a platform for trench/fin-based devices that require vertical, smooth sidewall structures free of plasma damage.

Conclusion

We proposed the ($\bar{1}12$) orientation as a suitable crystallographic plane for homoepitaxy and selective-area gas etching of $\beta\text{-Ga}_2\text{O}_3$, and demonstrated its advantages for both growth and etching using our HCl-based HVPE system. In homoepitaxy, we achieved twin-free growth without miscut control and an atomically flat surface characterized by a well-ordered step-and-terrace morphology. Furthermore, the Cl impurity incorporation attributed to HVPE was sufficiently low, in the low- 10^{15} cm^{-3} range. In gas etching, we confirmed that anisotropic etching with a high vertical-to-lateral etch-rate ratio of approximately 50 was possible owing to the formation of vertical, extremely flat (100)-faceted sidewalls when the etching mask windows were aligned along the $[02\bar{1}]$ direction. Taken together, these growth and etching results underscore the potential of the ($\bar{1}12$) plane for $\beta\text{-Ga}_2\text{O}_3$ power devices that require high-purity, smooth homoepitaxial layers, and high-aspect-ratio trench/fin structures with vertical and flat sidewalls without plasma damage.

Acknowledgments

Authors thank T. Harada at NIMS for the use of the XRD measurement instrument. This study was supported by the

Nanofabrication and Electron Microscopy Units at NIMS within the framework of the Advanced Research Infrastructure for Materials and Nanotechnology (ARIM), supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan (No. JPMXP1225NM5079).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was financially supported by a Grant-in-Aid for Scientific Research (B) from the Japan Society for the Promotion of Science (JSPS), MEXT, Japan (No. JP24K01368), and by a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO), Ministry of Economy, Trade and Industry (METI), Japan (No. JPNP22007).

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References

- [1] Sasaki K. Prospects for $\beta\text{-Ga}_2\text{O}_3$: now and into the future. *Appl Phys Express*. 2024;17(9):090101. doi: 10.35848/1882-0786/ad6b73
- [2] Onuma T, Saito S, Sasaki K, et al. Valence band ordering in $\beta\text{-Ga}_2\text{O}_3$ studied by polarized transmittance and reflectance spectroscopy. *Jpn J Appl Phys*. 2015;54(11):112601. doi: 10.7567/JJAP.54.112601
- [3] Higashiwaki M, Sasaki K, Kuramata A, et al. Gallium oxide (Ga_2O_3) metal-semiconductor field-effect transistors on single-crystal $\beta\text{-Ga}_2\text{O}_3$ (010) substrates. *Appl Phys Lett*. 2012;100(1):013504. doi: 10.1063/1.3674287
- [4] Villora EG, Shimamura K, Yoshikawa Y, et al. Large-size $\beta\text{-Ga}_2\text{O}_3$ single crystals and wafers. *J Cryst Growth*. 2004;270(3–4):420. doi: 10.1016/j.jcrysgro.2004.06.027
- [5] Galazka Z, Irmscher K, Uecker R, et al. On the bulk $\beta\text{-Ga}_2\text{O}_3$ single crystals grown by the Czochralski method. *J Cryst Growth*. 2014;404:184. doi: 10.1016/j.jcrysgro.2014.07.021
- [6] Kuramata A, Koshi K, Watanabe S, et al. High-quality $\beta\text{-Ga}_2\text{O}_3$ single crystals grown by edge-defined film-fed growth. *Jpn J Appl Phys*. 2016;55(12):1202A2. doi: 10.7567/JJAP.55.1202A2
- [7] Hoshikawa K, Ohba E, Kobayashi T, et al. Growth of $\beta\text{-Ga}_2\text{O}_3$ single crystals using vertical Bridgman method in ambient air. *J Cryst Growth*. 2016;447:36–41. doi: 10.1016/j.jcrysgro.2016.04.022
- [8] Igarashi T, Ueda Y, Koshi K, et al. Growth of 6 inch diameter $\beta\text{-Ga}_2\text{O}_3$ crystal by the vertical Bridgman method. *Phys Status Solidi*. 2025;262(8):2400444. doi: 10.1002/pssb.202400444
- [9] Yoshikawa A, Kochurikhin V, Tomida T, et al. Growth of bulk $\beta\text{-Ga}_2\text{O}_3$ crystals from melt without

- precious-metal crucible by pulling from a cold container. *Sci Rep.* **2024**;14(1):14881. doi: [10.1038/s41598-024-65420-7](https://doi.org/10.1038/s41598-024-65420-7)
- [10] Murakami H, Nomura K, Goto K, et al. Homoepitaxial growth of β -Ga₂O₃ layers by halide vapor phase epitaxy. *Appl Phys Express.* **2015**;8(1):015503. doi: [10.7567/APEX.8.015503](https://doi.org/10.7567/APEX.8.015503)
 - [11] Goto K, Konishi K, Murakami H, et al. Halide vapor phase epitaxy of Si doped β -Ga₂O₃ and its electrical properties. *Thin Solid Films.* **2018**;666(September):182. doi: [10.1016/j.tsf.2018.09.006](https://doi.org/10.1016/j.tsf.2018.09.006)
 - [12] Goto K, Murakami H, Kuramata A, et al. Effect of substrate orientation on homoepitaxial growth of β -Ga₂O₃ by halide vapor phase epitaxy. *Appl Phys Lett.* **2022**;120(10):102102. doi: [10.1063/5.0087609](https://doi.org/10.1063/5.0087609)
 - [13] Ema K, Sasaki K, Kuramata A, et al. Homo- and hetero-epitaxial growth of β -gallium oxide via GaCl₃-O₂-N₂ system. *J Cryst Growth.* **2021**;564:564 126129. doi: [10.1016/j.jcrysgro.2021.126129](https://doi.org/10.1016/j.jcrysgro.2021.126129)
 - [14] Nitta K, Sasaki K, Kuramata A, et al. Investigation of high speed β -Ga₂O₃ growth by solid-source trihalide vapor phase epitaxy. *Jpn J Appl Phys.* **2023**;62(SF):SF1021. doi: [10.35848/1347-4065/acc747](https://doi.org/10.35848/1347-4065/acc747)
 - [15] Oshima Y, Oshima T. Rapid homoepitaxial growth of (011) β -Ga₂O₃ by HCl-based halide vapor phase epitaxy. *Sci Technol Adv Mater.* **2025**;26(1):2585551. doi: [10.1080/14686996.2025.2585551](https://doi.org/10.1080/14686996.2025.2585551)
 - [16] Oshima Y, Oshima T. Homoepitaxial growth of (-102) β -Ga₂O₃ by halide vapor phase epitaxy. *Semicond Sci Technol.* **2023**;38(10):105003. doi: [10.1088/1361-6641/acf241](https://doi.org/10.1088/1361-6641/acf241)
 - [17] Yoshinaga J, Tozato H, Okuyama T, et al. High-speed growth of thick high-purity β -Ga₂O₃ layers by low-pressure hot-wall metalorganic vapor phase epitaxy. *Appl Phys Express.* **2023**;16(9):095504. doi: [10.35848/1882-0786/acf8ae](https://doi.org/10.35848/1882-0786/acf8ae)
 - [18] Yoshinaga J, Iba Y, Kubota K, et al. Homoepitaxial growth of thick Si-doped β -Ga₂O₃ layers using tetramethylsilane as a dopant source by low-pressure hot-wall metalorganic vapor phase epitaxy. *Appl Phys Express.* **2025**;18(5):055503. doi: [10.35848/1882-0786/adcfee](https://doi.org/10.35848/1882-0786/adcfee)
 - [19] Nishinaka H, Nagaoka T, Kajita Y, et al. Rapid homoepitaxial growth of (010) β -Ga₂O₃ thin films via mist chemical vapor deposition. *Mater Sci Semicond Process.* **2021**;128(2020):105732. doi: [10.1016/j.mssp.2021.105732](https://doi.org/10.1016/j.mssp.2021.105732)
 - [20] Oshima T, Arai N, Suzuki N, et al. Surface morphology of homoepitaxial β -Ga₂O₃ thin films grown by molecular beam epitaxy. *Thin Solid Films.* **2008**;516(17):5768. doi: [10.1016/j.tsf.2007.10.045](https://doi.org/10.1016/j.tsf.2007.10.045)
 - [21] Sasaki K, Kuramata A, Masui T, et al. Device-quality β -Ga₂O₃ epitaxial films fabricated by ozone molecular beam epitaxy. *Appl Phys Express.* **2012**;5(3):035502. doi: [10.1143/APEX.5.035502](https://doi.org/10.1143/APEX.5.035502)
 - [22] Vogt P, Mauze A, Wu F, et al. Metal-oxide catalyzed epitaxy (mocataxy): the example of the O plasma-assisted molecular beam epitaxy of β -(Al_xGa_{1-x})₂O₃ / β -Ga₂O₃ heterostr. *Appl Phys Express.* **2018**;11(11):115503. doi: [10.7567/APEX.11.115503](https://doi.org/10.7567/APEX.11.115503)
 - [23] Vogt P, Hensling FVE, Azizie K, et al. Adsorption-controlled growth of Ga₂O₃ by suboxide molecular-beam epitaxy. *APL Mater.* **2021**;9(3):031101. doi: [10.1063/5.0035469](https://doi.org/10.1063/5.0035469)
 - [24] Wakabayashi R, Oshima T, Hattori M, et al. Oxygen-radical-assisted pulsed-laser deposition of β -Ga₂O₃ and β -(Al_xGa_{1-x})₂O₃ films. *J Cryst Growth.* **2015**;424(15):77. doi: [10.1016/j.jcrysgro.2015.05.005](https://doi.org/10.1016/j.jcrysgro.2015.05.005)
 - [25] Oshima T, Okuno T, Arai N, et al. β -Al_{2x}Ga_{2-2x}O₃ thin film growth by molecular beam epitaxy. *Jpn J Appl Phys.* **2009**;48(7):070202. doi: [10.1143/JJAP.48.070202](https://doi.org/10.1143/JJAP.48.070202)
 - [26] Wakabayashi R, Yoshimatsu K, Hattori M, et al. Epitaxial stabilization of complete solid-solution β -(Al_xGa_{1-x})₂O₃ (100) films by pulsed-laser deposition. *Cryst Growth Des.* **2021**;21(5):2844. doi: [10.1021/acs.cgd.1c00030](https://doi.org/10.1021/acs.cgd.1c00030)
 - [27] Koreishi K, Soma T, Kumigashira H, et al. Epitaxial growth and band offsets of β -(Sc_xGa_{1-x})₂O₃ thin films grown on (100) β -Ga₂O₃ substrate. *Appl Phys Lett.* **2024**;125(15):152101. doi: [10.1063/5.0226675](https://doi.org/10.1063/5.0226675)
 - [28] Koreishi K, Soma T, Ohtomo A. Structural and electrical properties of (100) β -(Sc_xGa_{1-x})₂O₃/Ga₂O₃ heterojunctions. *J Appl Phys.* **2025**;138(1):015302. doi: [10.1063/5.0277701](https://doi.org/10.1063/5.0277701)
 - [29] Oshima T, Fujita S. Properties of Ga₂O₃-based (In_xGa_{1-x})₂O₃ alloy thin films grown by molecular beam epitaxy. *Phys Status Solidi.* **2008**;5(9):3113. doi: [10.1002/pssc.200779297](https://doi.org/10.1002/pssc.200779297)
 - [30] Nishinaka H, Kajita Y, Hosaka S, et al. Composition analysis of β -(In_xGa_{1-x})₂O₃ thin films coherently grown on (010) β -Ga₂O₃ via mist CVD. *Sci Technol Adv Mater.* **2024**;25(1):614. doi: [10.1080/14686996.2024.2414733](https://doi.org/10.1080/14686996.2024.2414733)
 - [31] Kita K, Suzuki E, Mao Q. Study on the effects of post-deposition annealing on SiO₂/ β -Ga₂O₃ MOS characteristics. *ECS Trans.* **2019**;92(1):59. doi: [10.1149/09201.0059ecst](https://doi.org/10.1149/09201.0059ecst)
 - [32] Kobayashi T, Maeda K, Hara M, et al. Formation of high-quality SiO₂/ β -Ga₂O₃ (001) MOS structures: the role of post-deposition annealing. *Appl Phys Lett.* **2025**;126(1):012108. doi: [10.1063/5.0245289](https://doi.org/10.1063/5.0245289)
 - [33] Maeda K, Kobayashi T, Hara M, et al. Hydrogen passivation of electron traps and fixed charges in SiO₂/ β -Ga₂O₃ (001) MOS structures. *Appl Phys Lett.* **2025**;127(11):112107. doi: [10.1063/5.0287823](https://doi.org/10.1063/5.0287823)
 - [34] Sasaki K, Higashiwaki M, Kuramata A, et al. Si-ion implantation doping in β -Ga₂O₃ and its application to fabrication of low-resistance ohmic contacts. *Appl Phys Express.* **2013**;6(8):086502. doi: [10.7567/APEX.6.086502](https://doi.org/10.7567/APEX.6.086502)
 - [35] Wong MH, Lin C-H, Kuramata A, et al. Acceptor doping of β -Ga₂O₃ by Mg and N ion implantations. *Appl Phys Lett.* **2018**;113(10):102103. doi: [10.1063/1.5050040](https://doi.org/10.1063/1.5050040)
 - [36] Xu W, Wang Y, You T, et al. First demonstration of waferscale heterogeneous integration of Ga₂O₃ MOSFETs on SiC and Si substrates by ion-cutting process. In: 2019 IEEE International Electron Devices Meeting (IEDM); San Francisco, CA, USA. Decem IEEE; **2019**. p. 12.5.1–12.5.4. doi: [10.1109/IEDM19573.2019.8993501](https://doi.org/10.1109/IEDM19573.2019.8993501)
 - [37] Schewski R, Baldini M, Irmscher K, et al. Evolution of planar defects during homoepitaxial growth of β -Ga₂O₃ layers on (100) substrates—a quantitative model. *J Appl Phys.* **2016**;120(22):225308. doi: [10.1063/1.4971957](https://doi.org/10.1063/1.4971957)
 - [38] Ngo TS, Le DD, Lee J, et al. Investigation of defect structure in homoepitaxial (-201) β -Ga₂O₃ layers prepared. *J Alloys Compd.* **2020**;834(5):155027. doi: [10.1016/j.jallcom.2020.155027](https://doi.org/10.1016/j.jallcom.2020.155027)
 - [39] Thieu QT, Wakimoto D, Koishikawa Y, et al. Preparation of 2-in.-diameter (001) β -Ga₂O₃

- homoepitaxial wafers by halide vapor phase epitaxy. *Jpn J Appl Phys.* **2017**;56(11):110310. doi: [10.7567/JJAP.56.110310](https://doi.org/10.7567/JJAP.56.110310)
- [40] Yang J, Ahn S, Ren F, et al. High reverse breakdown voltage Schottky rectifiers without edge termination on Ga₂O₃. *Appl Phys Lett.* **2017**;110(19):192101. doi: [10.1063/1.4983203](https://doi.org/10.1063/1.4983203)
- [41] Mu S, Wang M, Peelaers H, et al. First-principles surface energies for monoclinic Ga₂O₃ and Al₂O₃ and consequences for cracking of (Al_xGa_{1-x})₂O₃. *APL Mater.* **2020**;8(9):091105. doi: [10.1063/5.0019915](https://doi.org/10.1063/5.0019915)
- [42] Hossain SMM, Yu DS, Alam S, et al. Metalorganic chemical vapor deposition of (011) β-Ga₂O₃ films with 20 μm drift layer. *ACS Appl Electron Mater.* **2026**;8(3):1380. doi: [10.1021/acsaelm.5c02627](https://doi.org/10.1021/acsaelm.5c02627)
- [43] Oshima T. Mapping primary crystallographic planes in β-Ga₂O₃ based on a pseudo-cubic oxygen sublattice. *Jpn J Appl Phys.* **2026**;65(3):038003. doi: [10.35848/1347-4065/ae42ac](https://doi.org/10.35848/1347-4065/ae42ac)
- [44] Oshima T, Oshima Y. Fabrication of air bridges on (100) β-Ga₂O₃ using crystallographic HCl gas etching. *AIP Adv.* **2025**;15(5):055207. doi: [10.1063/5.0260753](https://doi.org/10.1063/5.0260753)
- [45] Oshima Y, Kawara K, Oshima T, et al. Rapid growth of α-Ga₂O₃ by HCl-boosted halide vapor phase epitaxy and effect of precursor supply conditions on crystal properties. *Semicond Sci Technol.* **2020**;35(5):055022. doi: [10.1088/1361-6641/ab7843](https://doi.org/10.1088/1361-6641/ab7843)
- [46] Hinuma Y, Kamachi T, Hamamoto N, et al. Surface oxygen vacancy formation energy calculations in 34 orientations of β-Ga₂O₃ and θ-Al₂O₃. *J Phys Chem C.* **2020**;124(19):10509. doi: [10.1021/acs.jpcc.0c00994](https://doi.org/10.1021/acs.jpcc.0c00994)
- [47] Oshima T, Oshima Y. Selective area growth of β-Ga₂O₃ by HCl-based halide vapor phase epitaxy. *Appl Phys Express.* **2022**;15(7):075503. doi: [10.35848/1882-0786/ac75c8](https://doi.org/10.35848/1882-0786/ac75c8)
- [48] Konishi K, Goto K, Togashi R, et al. Comparison of O₂ and H₂O as oxygen source for homoepitaxial growth of β-Ga₂O₃ layers by halide vapor phase epitaxy. *J Cryst Growth.* **2018**;492:39–44. doi: [10.1016/j.jcrysgro.2018.04.009](https://doi.org/10.1016/j.jcrysgro.2018.04.009)
- [49] Oshima T, Oshima Y. Anisotropic non-plasma HCl gas etching of a (010) β-Ga₂O₃ substrate. *Appl Phys Express.* **2023**;16(6):066501. doi: [10.35848/1882-0786/acdbb7](https://doi.org/10.35848/1882-0786/acdbb7)
- [50] Oshima T, Oshima Y. Plasma-free dry etching of (001) β-Ga₂O₃ substrates by HCl gas. *Appl Phys Lett.* **2023**;122(16):162102. doi: [10.1063/5.0138736](https://doi.org/10.1063/5.0138736)
- [51] Oshima Y, Oshima T. Effect of the temperature and HCl partial pressure on selective-area gas etching of (001) β-Ga₂O₃. *Jpn J Appl Phys.* **2023**;62(8):080901. doi: [10.35848/1347-4065/acee3b](https://doi.org/10.35848/1347-4065/acee3b)
- [52] Oshima T, Oshima Y. Fabrication of β-Ga₂O₃/air-gap structures on (001) β-Ga₂O₃ using HCl gas etching. *Sci Technol Adv Mater Methods.* **2025**;5(1):2554046. doi: [10.1080/27660400.2025.2554046](https://doi.org/10.1080/27660400.2025.2554046)
- [53] Oshima Y, Oshima T. HCl-gas etching behavior of (001) β-Ga₂O₃ under oxygen supply. *Sci Technol Adv Mater.* **2025**;26(1):2546285. doi: [10.1080/14686996.2025.2546285](https://doi.org/10.1080/14686996.2025.2546285)
- [54] Oshima T, Oshima Y. Using selective-area growth and selective-area etching on (−102) β-Ga₂O₃ substrates to fabricate plasma-damage-free vertical fins and trenches. *Appl Phys Lett.* **2024**;124(4):042110. doi: [10.1063/5.0186319](https://doi.org/10.1063/5.0186319)
- [55] Oshima T, Oshima Y. Near-vertical plasma-free HCl gas etching on (011) β-Ga₂O₃. *Jpn J Appl Phys.* **2025**;64(1):018003. doi: [10.35848/1347-4065/ada706](https://doi.org/10.35848/1347-4065/ada706)
- [56] Oshima T, Togashi R, Oshima Y. Plasma-free anisotropic selective-area etching of β-Ga₂O₃ using forming gas under atmospheric pressure. *Sci Technol Adv Mater.* **2024**;25(1):2378683. doi: [10.1080/14686996.2024.2378683](https://doi.org/10.1080/14686996.2024.2378683)