

Supplementary file

Plasma-free dry etching of (001) β -Ga₂O₃ substrates by HCl gas

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HCl gas etching rate of the (001) surface as a function of reactor temperature

We performed HCl gas etching for SiO₂-masked (001) substrates at different temperatures and measured the depths of the etched depressions formed in the square windows ($100 \times 100 \mu\text{m}^2$) using a stylus profiler to understand the effect of temperature on the etching rate for the (001) surface. Figure S1 shows the obtained etching rate as a function of the reactor temperature. The etching rate monotonically increased with the reactor temperature. In the study, we focused on the substrate etched with the highest rate of ~ 170 nm/min at 1038°C and discussed the etched structures.

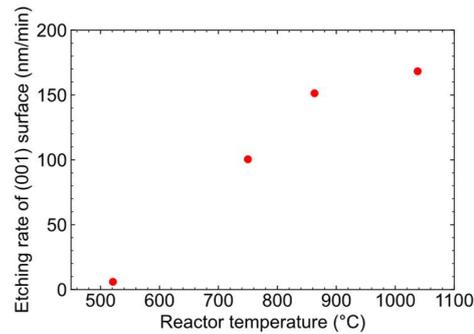


FIG. S1. Etching rate of (001) surface as a function of reactor temperature.

Etched structures after the removal of the SiO₂ mask

For better understanding the etched structures, particularly, sidewall morphologies, we removed the SiO₂ mask using buffered hydrofluoric acid and performed SEM observation again (Figures S2–S5).

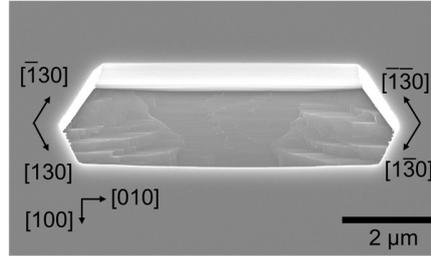


FIG. S2. Top-view scanning electron microscopy images of the etched trench formed under the dot pattern, corresponding to Fig. 1(a) and 1(b). Note that the pattern was not exactly the same one of the Fig. 1(a) and 1(b).

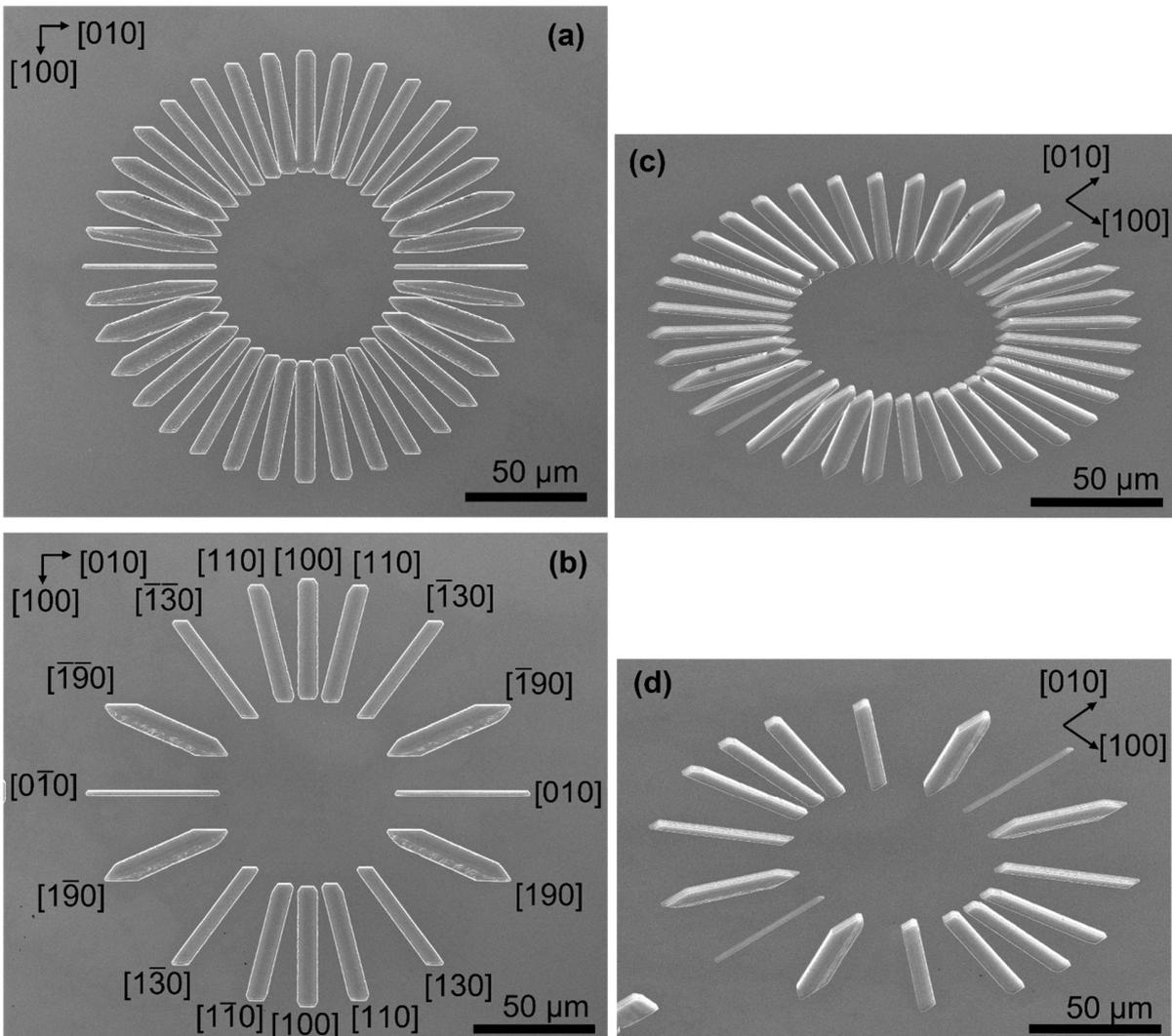


FIG. S3. (a) and (b) Top-view scanning electron microscopy images of the etched trenches on the radial-line-patterns, corresponding to Figs. 2 (a) and 2(b), respectively. (c) and (d) are tilted view (50° from the surface normal) of (a) and (b), respectively.

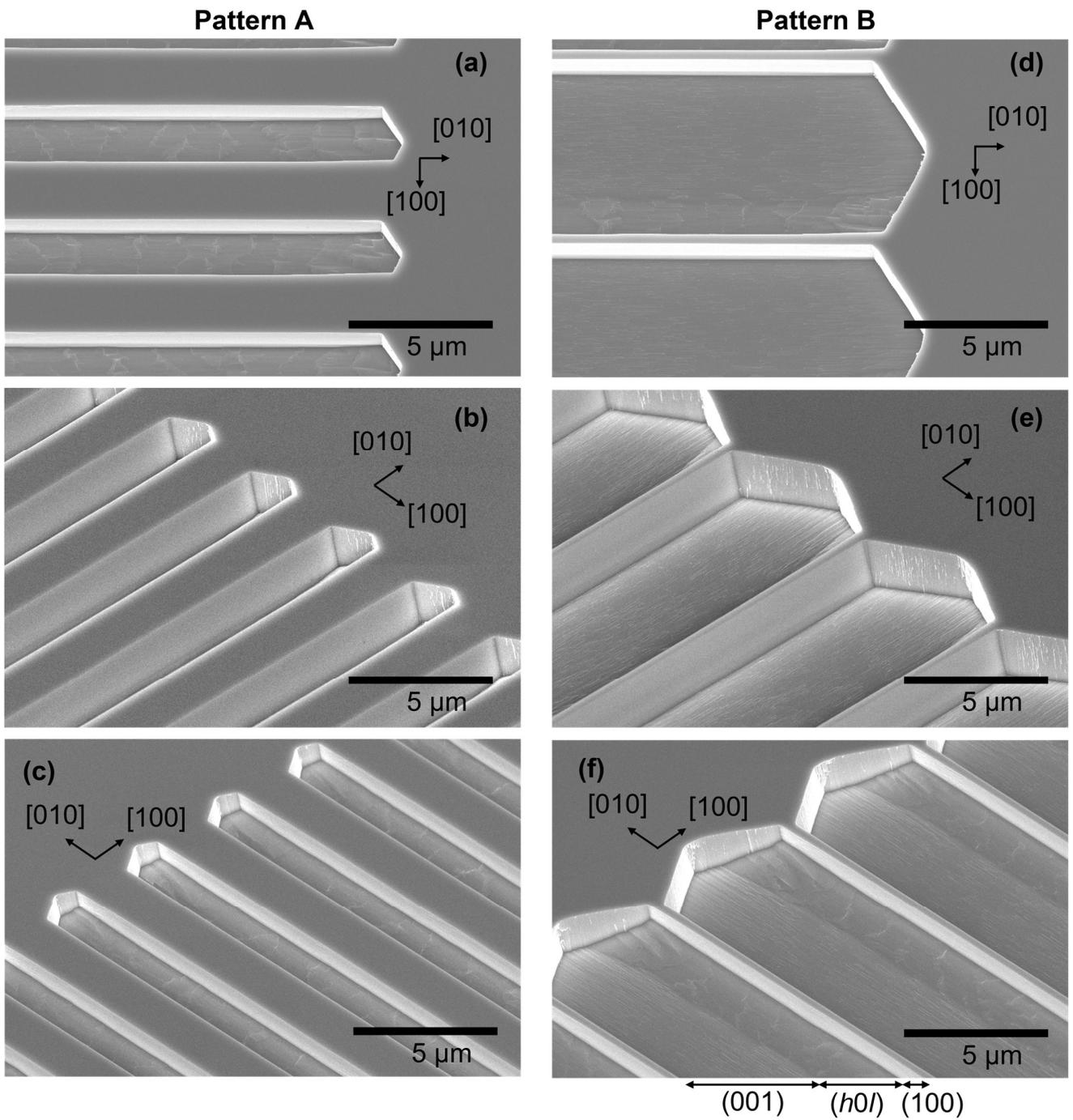


FIG. S4. Top- and tilted-view of scanning electron microscopy images (0° and 50° from the surface normal, respectively) of etched trenches produced using the $[010]$ -oriented stripe masks of (a)–(c) pattern A and (d)–(f) pattern B, corresponding to Figs. 3(a)–3(c) and 3(d)–3(f), respectively.

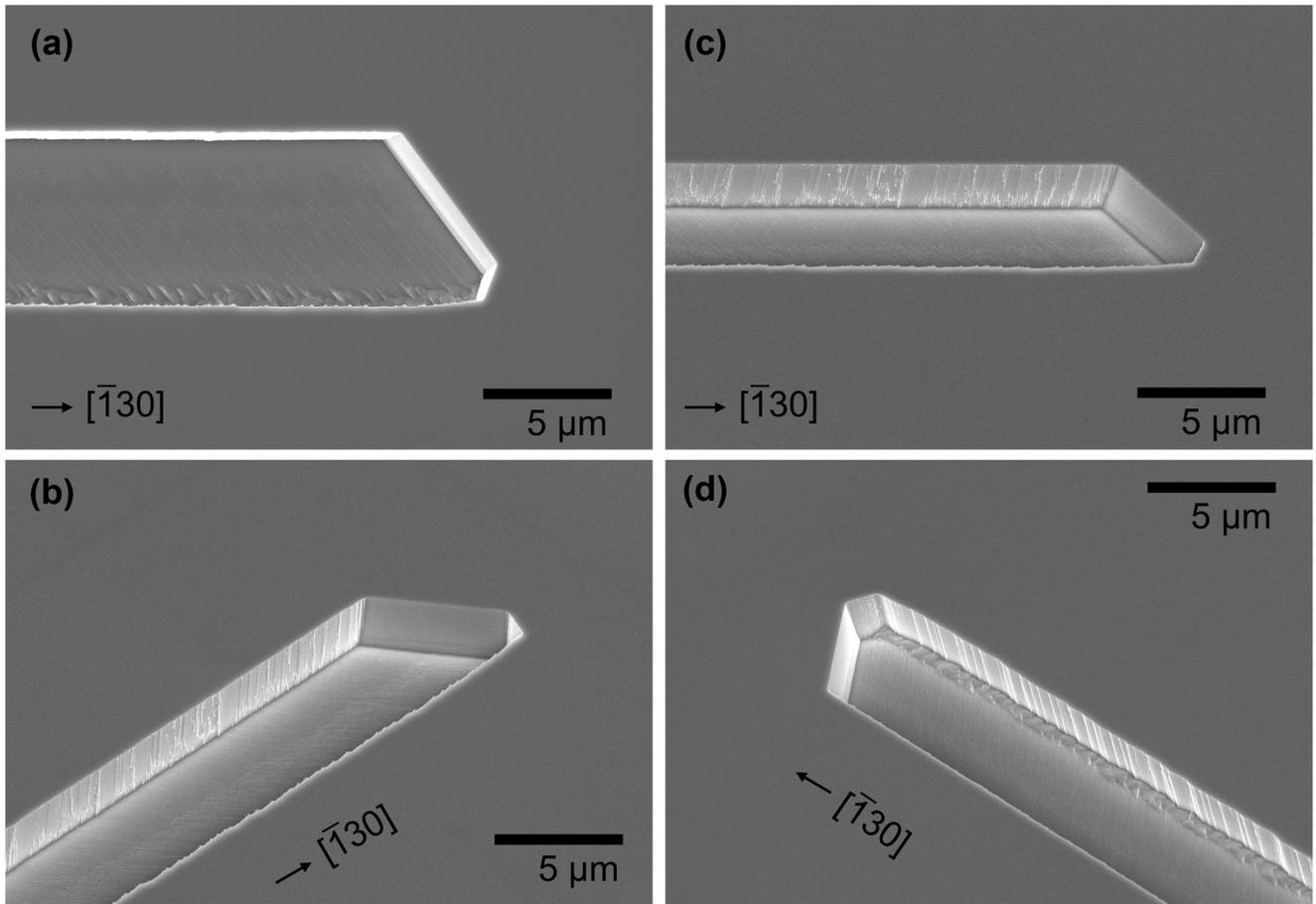


FIG. S5. Scanning electron microscopy images of a single etched trench along $[\bar{1}30]$, which is one of the radial lines in Figs. S3(b) and S3(d). (a) is top view and (b)–(d) are tilted view (50° from the surface normal) observed from the different in-plane directions. The sidewalls along $[\bar{1}30]$ were formed with (310) facets. The macro steps appeared on the (310) facet surfaces may be caused by the emergence of (100) facets.

Surface morphology of the etched (001) surface

Surface morphology of the etched (001) surface was observed using atomic force microscopy (FIG. S6). See the text in the paper for the detail description of the morphology.

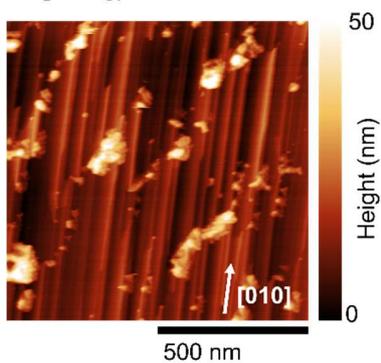


FIG. S6. Atomic force microscopy image of the (001) surface after HCl etching at 1038°C.