# Fabrication of Gallium Nitride Deep-Trench Structures by Photoelectrochemical Etching

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**Keywords: Gallium Nitride, Etching, Photoelectrochemistry, Trench Structure, Power Device, Superjunction**

**Abstract**

**Photo-electrochemical (PEC) etching was used to fabricate deep trench structures in a GaN-on-GaN epilayer grown on n-GaN substrates. A 50-nm thick Ti layer used for an etching mask was not removed even after etching to a depth of > 30 μm. The width of the side etching was less than 1 μm with high accuracy. The aspect ratio (depth/with) of 3.3-μm-wide trench with a PEC etching depth of 24.3 μm was 7.3. These results demonstrate the excellent potential of PEC etching for fabricating deep trenches in vertical GaN devices.**

## INTRODUCTION

Gallium nitride (GaN) vertical power devices have recently attracted much attention as energy-saving solutions because of their many advantages in terms of a low specific on-resistance ($R_{on}$) coupled with a high breakdown voltage ($V_B$) [1]. In addition, superjunction (SJ) structures have been developed in power semiconductor devices in order to outperform the unipolar operating limits [2,3]. In SJ structures, p / n columns are used instead of a unipolar drift layer. It has recently been demonstrated that SJ structures with 25-μm-deep trenched can be fabricated even in wide-band-gap semiconductors such as silicon carbide (SiC) [4]. As a technical aspect, it is necessary to fabricate deep trench structures in an n-type layer with an aspect ratio (depth / width) of more than 10, an aperture width of 1–2 μm, and backfilling regrowth of a p-type layer. In GaN, although there is a theoretical report [5], that of device fabrication is limited in lateral SJ devices [6]. There is no report on the actual fabrication of GaN vertical SJ devices, because it is difficult to achieve deep trench etching. Generally, GaN is etched by inductively coupled plasma reactive-ion etching [7,8]. Unfortunately, however, plasma readily causes damage to GaN, and there is low etching selectivity between the GaN and the etching mask.

Photoelectrochemical (PEC) etching might solve these problems [9–12], as it has excellent etching selectivity against the etching mask and is less likely to cause damage because it is plasma free. PEC etching has recently been applied to the mesa fabrication of GaN pn-junction diodes (PNDs) with high $V_B$ values [13]. Furthermore, PEC etching produces greater yields of high-$V_B$ devices than does the dry etching of GaN-PMDs. Other applications of PEC etching include gate-recess etching for AlGaN/GaN high-electron-mobility transistors (HEMTs) [9]. In particular, PEC etching has many advantages from the viewpoint of preventing damage to fabricated products because it is a plasma-free process. Here, we report the use of PEC etching in the fabrication of deep-trench structures in a GaN-on-GaN epilayer.

## EXPERIMENTAL DETAILS

PEC etching of GaN proceeds by photo-assisted anodic oxidation. GaN is dissolved as $Ga^{3+}$ ions, owing to holes excited by UV irradiation at the anode of the GaN/electrolyte interface. The resulting $Ga^{3+}$ ions react with hydroxide ions ($OH^-$) in the electrolyte to form $Ga_2O_3$. This dissolves in acid or base, so that an anodic oxidation process is the basis of the PEC etching of GaN [9,11,14].

Epitaxial layers with the structures of Schottky barrier diodes (SBDs) and PNDs were grown by metalorganic vapor-phase epitaxy on n-GaN substrates. The SBDs consisted of an n-GaN layer with a nominal Si concentration of $1.5 \times 10^{16}$ $cm^{-3}$ and a thickness of 5.8 μm. The PNDs consisted of a Mg-doped ($2 \times 10^{20}$ $cm^{-3}$ with 20 nm thickness and $5 \times 10^{18}$ $cm^{-3}$ with 500 nm thickness) layer of GaN on an $n^-$-drift layer of Si-doped ($2 \times 10^{16}$ $cm^{-3}$ with 10 μm thickness) GaN. A 2-μm-thick $n^+$-interlayer was grown between the $n^-$-drift layer and the n-type GaN substrate. The PNDs were annealed at 850 °C for 30 min in $N_2$ to activate the Mg acceptors before the mask-patterning process. The etching mask was a 50-nm-thick layer of Ti produced by vacuum evaporation with lift-off.

In the PEC etching, the electrolyte was 0.01 M aqueous NaOH solution containing 1% Triton X-100 [4-(1,1,3,3-tetramethylbutyl) phenylpoly (ethylene glycol)] nonionic surfactant was used as a wetting agent to reduce surface tension and to assist in bubble removal from the epi surface. A Pt counter electrode was used as the cathode. The anode was a GaN epi surface with a back-side ohmic contact on the substrate. The etching voltage was biased between the GaN epi surface and the Pt counter electrode. The intensity of UV illumination from a Hg–Xe lamp was 9.0 mW/$cm^2$. A pulsed PEC mode was used in which the UV irradiation and the etching voltage were both applied simultaneously during the

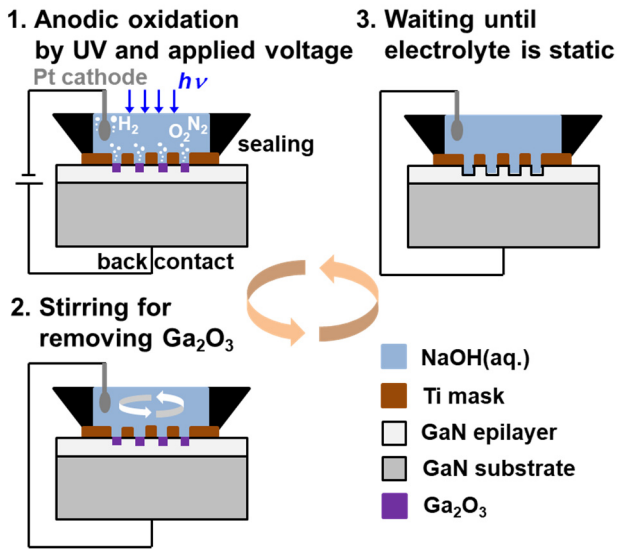


Fig. 1. Schematic representation of the photoelectrochemical (PEC) etching of GaN [12]

PEC step only, and the electrolyte was refilled by using a pump after the PEC step. The next PEC step was started after an interval, because it was necessary to wait until the electrolyte was static. A schematics representation of the PEC etching process is shown in Fig. 1. More details of the procedure can be found elsewhere [11,12].

## RESULTS

First, we confirmed the adhesion between Ti mask and the p-type layer of PNDs during the PEC etching process by using a circular dot mask pattern, because this interface is probably the weakest point in side etching owing to the existence of holes. To demonstrate the potential of PEC etching in deep trench fabrication, PEC etching was conducted to an etching depth of more than 20 μm. Figure 2(a) shows scanning electron microscopy (SEM) images of typical cylinder-shaped PND patterns produced by PEC etching. The size of the etched region remained almost the same as that of the etching mask, even after etching to a depth of over 20 μm. The width of the side etching was less than 1 μm, with high accuracy. Although it was difficult to exactly evaluate the residual thickness of Ti, the estimated etching selectivity against an etching mask of Ti was >400 (~20 μm/50 nm). The etching rate was approximately 25 nm/min, which was comparable to that of conventional dry etching.

Figure 2(b) shows SEM images of a PEC-etched cavity-shaped SBD pattern with an etching depth of approximately 7.7 μm, as an example of a negative–positive reversal pattern. The diameters of the circular cavities were designed to be 1, 5, 10, and 20 μm. The side walls are almost vertical, and there are small bumps on the bottom of the circular cavities of 20 μm diameter.

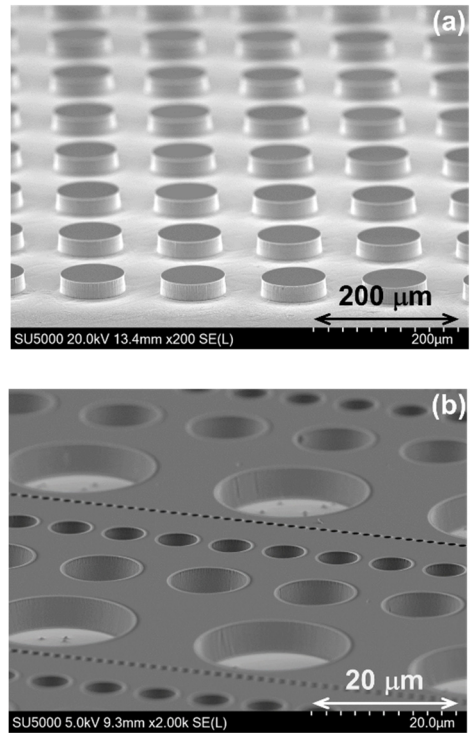


Fig. 2. SEM images of PEC-etched cylinder-shaped (a) and cavity-shaped GaN patterns (b) [12]

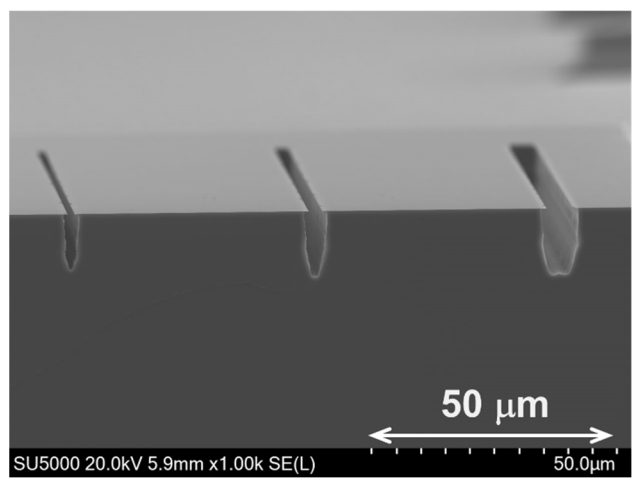


Fig. 3. Typical cross-sectional SEM images of PEC-etched GaN trench patterns

Dark spots were observed in SEM-cathodoluminescence images of the center of bumps; therefore, the origins of the bumps were dislocations that cause short lifetimes. These PEC-etched cylinder and cavity shapes are independent of the crystallographic orientation; this also indicates that the width of side etching is determined by the hole lifetime.

GaN vertical trenches were fabricated by using Ti line masks with widths of 1.4, 2.8, or 5.6 μm on SBDs epi wafer. Figure 3 shows typical cross-sectional SEM images of the trenches produced by PEC etching, cleaved along the *m*-face. Remarkably, each trench had almost the same PEC etching depth of around 7.7 μm; in other words, the depth-etching rate in each pulsed step was controlled by changing the current density. Figure 4 shows the relationship between the PEC etching depth $W_r$ and the trench aspect ratio. Unfortunately, there are only a few reports on the fabrication of GaN vertical trenches. Previously reported GaN trench depths were approximately 1–3 μm with aspect ratios of 1–3. We therefore used SiC trench structures fabricated by ICP-RIE as our reference structures [4,15,16]. In Fig. 4, the solid, dashed, and dotted lines correspond to estimates of the aspect ratio of PEC etching based on $W_r = (W_{mask} + 2W_{side\text{-}etching})$, where $W_{mask}$ is the width of the Ti etching mask and $W_{side\text{-}etching}$ is the amount of side etching. The width of the side etching was assumed to be 0.7 μm from Fig. 3. The filled symbols are the experimental data, which are consistent with the estimated values. With short-width aperture masks, the PEC etching rate showed a decrease at an etching depth of about 30 μm, because the UV radiation appeared to have difficulty in reaching the bottom of these deep trenches. This indicates that a coherent UV light source would be preferable for deep PEC etching. As a matter of fact, from Fig. 4, these results indicate that PEC etching has excellent potential for deep trench etching. The aspect ratio (depth/width) of the trenches was more than 7 at an etching depth in excess of 20 μm. This aspect ratio and the etching depth are comparable to the best results for SiC trenches fabricated by ICP-RIE.

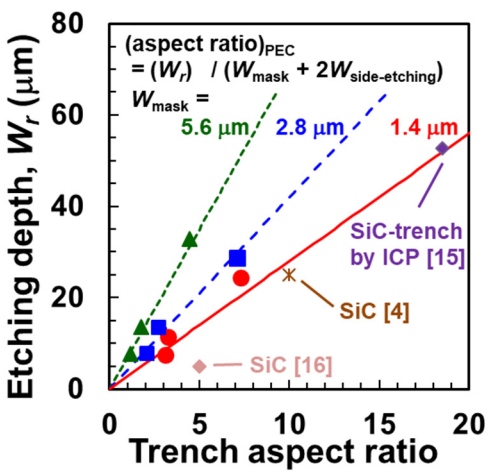


Fig. 4. Relationship between the PEC etching depth $W_r$ and the trench aspect ratio. The solid, dashed, and dotted lines correspond to estimates based on the hypothesis that the aspect ratio of PEC obeys $W_r = (W_{mask} + 2W_{side\text{-}etching})$. The width of the side etching was assumed to be 0.7 μm from Fig. 3. The filled symbols are experimental results [12]

In addition, these results indicate the excellent potential of PEC etching not only in the fabrication of optical and electronic devices, but also in fabricating GaN-micro-electromechanical-systems (MEMS) such as the through-via of wafers, diaphragms, microfluidic channels, and optical gratings. As an example, we demonstrated the potential of PEC etching in fabricating various patterns. Figure 5 shows examples of three PEC-etched patterns in GaN: the 'CS MANTECH', 'SCIOCS', and 'HOSEI Univ.' logos.

As ongoing challenge, we are trying to PEC etching on large-scale wafer. However, the conventional PEC etching requires three simultaneous actions:

(1) UV irradiation over the GaN bandgap energy,
(2) Sealing the electrolyte between the GaN surface anode and the cathode, and
(3) Electrical contact between the GaN anode and the cathode via an outside circuit.

These simultaneous requirements present a large constraint for experimental setups in large-scale wafer processes.

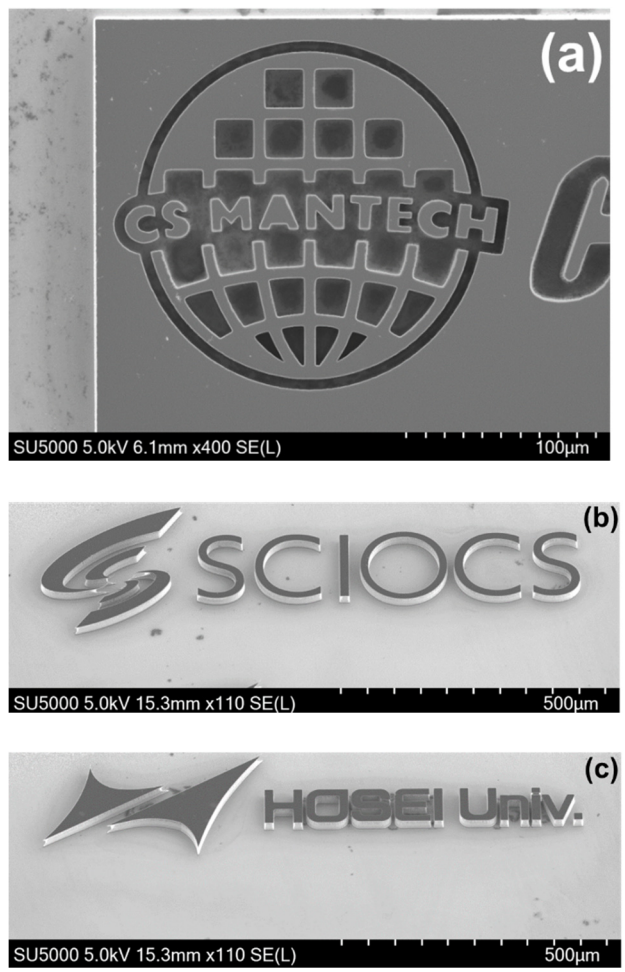


Fig. 5. SEM images of PEC-etched various GaN patterns: (a) 'CS MANTECH', (b) 'SCIOCS', and (c) 'HOSEI Univ.' logos

According to literature, Sulfate radicals ($SO4^{\bullet-}$) were used as the oxidizing agent; they consumed the extra UV photogenerated electrons, making it electrodeless [17,18]. We also succeeded in these simple electrodeless PEC-etching for wafer-process, in which the sample was only dipped into the electrolyte under UV irradiation [19,20]. We have plan to distributing this convenient PEC-etching technology to the GaN community as part of our responsibility as a GaN substrate supplier.

## CONCLUSIONS

We successfully fabricated deep-trench structures in GaN by PEC etching with a Ti mask. The aspect ratio of these trenches was more than 7 at an etching depth in excess of 20 μm. These results show that PEC etching can be applied to the fabrication of deep-trench structures in GaN for the manufacture of SJ devices.

## ACKNOWLEDGEMENTS

This research was supported by the Ministry of the Environment of Japan.

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