Various electrochemical conditions such as applied voltage $V_a$, UV-intensity $P_{UV}$, and anodization time $t_a$, were precisely controlled using a potentiostat connected to a computer system monitoring the anodic-reaction current density $J_a$. The structural properties of the GaN-porous samples formed under different conditions were compared using a scanning electron microscope (SEM) with a Hitachi SU-8010 system. Spectroscopic properties, such as photo-reflectance, transmittance, and absorbance, were evaluated using an HR4000CG-UV-NIR spectrometer (Ocean Optics) under the voltage applied in the same setup shown in Fig. 1.

Figures 2a–2d show top and cross-sectional SEM images of the GaN-porous samples formed after $t_a = 600$ and 1800 s by comparing between the FSI and BSI modes. The $V_a$ and $P_{UV}$ were adjusted by monitoring the $J_a$ to be about the same between both modes. No anodic current and no porous structure was observed at the same bias condition in the dark. For the FSI mode shown in Figs. 2a and 2b, the pore diameter measured from top images increased with anodization time, whereas the pore depth $d_p$ measured from the cross-section did not increase. On the other hand, $d_p$ increased with anodization time in BSI mode, as shown in Figs. 2c and 2d, where the pore was the almost the same throughout all parts of the porous layer.

Figure 3 shows the relationship between $d_p$ and the charge density $Q$ passing through the working electrode during the photo-assisted electrochemical process. In FSI mode, $d_p$ increased with $Q$ until around 400 mC/cm$^2$ ($t_a = 1200$ sec), but it largely decreased after that. In BSI mode, however, $d_p$ increased almost linearly with $Q$, showing no decrease in $Q$ over 1000 mC/cm$^2$ in this study. These results come from the difference in the supply method of holes used for the anodization reaction. The FSI mode generates holes near the top-surface due to FSI. As $Q$ increased to more than about 400 mC/cm$^2$ ($t_a = 1200$ sec), the pore wall thinned to breaking point and was removed from the top-surface. In BSI mode, on the other hand, the holes were...
supplied from the back surface or supplied only at the pore tips due to BSI. Since the anodic reaction occurred only at the pore tips, the pore was etched in the vertical direction, whose depth linearly increased with \( t \). From these results, we found that the BSI mode is very powerful for controlling the structural properties of GaN-porous structures such as pore diameter and \( d_p \) compared with the FSI mode.

The BSI mode was first reported on the formation of Si-porous structures.\(^{15}\) Light with photon energy \( h\nu \) above 1.43 eV was irradiated, whose energy was larger than the bandgap of Si. The holes generated at the back-surface diffused toward the pore tips to yield the anodic-reaction since the diffusion length of minority carriers in Si was long enough. However, the situation in BSI mode for GaN is quite different. Namely, the diffusion length of holes in n-type GaN is several hundred nm at most, which is much smaller than the sample thickness of 400 \( \mu \)m used in this study. In such a situation, the holes generated near the back-surface cannot contribute to the anodic reaction because they recombine until reaching the pore tips.

To clarify the formation mechanism of GaN-porous structures in BSI mode, we conducted the photo-assisted electrochemical process by changing monochromatic-light illumination using an optical filter. Table I summarizes the anodic-reaction \( J_a \) and the results of SEM observation on whether the porous structure was formed. The full width at half maximum of the band-path filter was 10 nm. From a series of experiments, we found that porous structures were formed on the GaN samples under monochromatic light with wavelengths of 370 and 380 nm, whereas neither porous formation nor anodic etching was observed at wavelengths of 350, 390, and 400 nm. It should be noted that the largest \( J_a \) was observed at a wavelength of 370 nm, corresponding to \( h\nu \) of 3.35 eV, which is smaller than the bandgap of GaN. These results clearly indicate that the light with \( h\nu \) below the bandgap contributes to the formation of GaN-porous structures in BSI mode.

The Franz-Keldysh effect is one possible phenomenon to explain the present results. Franz\(^{14}\) and Keldysh\(^{15}\) pointed out that the high electric field may cause a red-shift of the absorption edge, leading to the presence of absorption below the bulk bandgap. Cavallini et al. reported that the Franz-Keldysh effect is applicable for GaN nanowires to argue that the photo-absorption properties depended strongly on the wire diameter.\(^{16}\) We believe that this effect is similarly applicable to the present electrochemical process, where a high electric field is induced in the depletion region formed at the interface between the electrolyte and n-type GaN. In the depletion region, the Franz-Keldysh relative absorption coefficient \( \alpha \) is expressed as a function of both \( h\nu \) and \( V_a \), as follows:\(^{17,18}\)

\[
\alpha(h\nu, V_a) = \alpha_0 \exp \left( -\frac{h\nu - E_{gap}}{\Delta E(V_a)} \right),
\]

where \( E_{gap} \) is the bulk bandgap (= 3.44 eV for GaN) and \( \alpha_0 \) is the absorption coefficient at \( h\nu = E_{gap} \). The term \( \Delta E \) in Eq. 2 is the red-shift energy of the absorption edge and expressed by

\[
\Delta E(V_a) = \frac{2}{3} \left( \frac{\hbar \xi(V_a)}{m^*} \right)^{1/2},
\]

where \( \xi, m^*, q, \) and \( \hbar \) are the electric field, effective mass, elementary charge, and Dirac’s constant, respectively.

To experimentally elucidate the Franz-Keldysh effect, we conducted spectroscopic measurements on the GaN samples in the electrolyte under \( V_a \). Figure 4a shows the increases in photo-absorbance measured as a function of the wavelength of incident light, where the vertical axis shows the difference between the data obtained at \( V_a = 3 \) V and \( V_a = 0 \) V. The data clearly show that the red-shift of the absorption edge under \( V_a = 3 \) V was applied. The highest increase in absorbance was obtained at a wavelength of 370 nm, corresponding to the largest anodic-reaction current density obtained, as shown in Table I. The absorbance \( A(h\nu, V_a) \) is expressed as

\[
A(h\nu, V_a) = 1 - \exp \left( -\alpha(h\nu, V_a)W(V_a) \right),
\]

where \( W \) is the depletion layer width obtained by solving the Poisson’s equation in the depletion region. The solid line in Fig. 4a is the theoretical curve of the increase in absorbance obtained from Eq. 4 by considering the Franz-Keldysh effect expressed with Eqs. 2

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**Table I. Electrochemical conditions and results of anodic reactions**

<table>
<thead>
<tr>
<th>Wavelength (nm)/ Photon energy (eV)</th>
<th>Anodic-reaction current density ( J_a ) (A/cm²)</th>
<th>SEM observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>350/3.54</td>
<td>(&lt;10^{-6})</td>
<td>No structure</td>
</tr>
<tr>
<td>360/3.44</td>
<td>(0.54 - 1.69 \times 10^{-2})</td>
<td>Shallow etching</td>
</tr>
<tr>
<td>370/3.35</td>
<td>(2.76 - 8.39 \times 10^{-2})</td>
<td>Porous formation</td>
</tr>
<tr>
<td>380/3.26</td>
<td>(0.44 - 2.37 \times 10^{-4})</td>
<td>Porous formation</td>
</tr>
<tr>
<td>390/3.18</td>
<td>(&lt;10^{-6})</td>
<td>No structure</td>
</tr>
<tr>
<td>400/3.10</td>
<td>(&lt;10^{-6})</td>
<td>No structure</td>
</tr>
</tbody>
</table>
and 3. As shown in Fig. 4a, we found that the experimental data were well reproduced by the theoretical curve using the reasonable value of $\alpha_0 = 18000 \text{ cm}^{-1}$ at 3.44 eV for GaN.\cite{19} These results strongly suggest that the red-shift of the absorption edge observed for the formation of GaN-porous structures arises from the Franz-Keldysh effect.

On the basis of the above discussion, we propose a formation model of GaN-porous structures in BSI mode. Figure 4b shows our model with a schematic of a porous structure and its band-diagram during the photo-assisted electrochemical process. In the case of illumination with photon energy above the bulk bandgap $h\nu > E_{\text{gap}}$ the holes were generated near the back-surface due to so-called bandedge absorption (I). However, most of the holes were not involved in the anodic reaction since they recombined before reaching the reaction surface. For $E_{\text{gap}} - \Delta E < h\nu < E_{\text{gap}}$, the photons coming from the back-surface penetrated through the bulk GaN but were absorbed by Franz-Keldysh effect at the pore tips in which the high-electric field was induced under $V_a$ (II). In such a situation, the holes are generated only at the pore tips and contribute to the anodization of GaN and pore formation. For $h\nu < E_{\text{gap}} - \Delta E$, the photons obviously penetrate thorough both the bulk GaN and porous layer as transmitted light (III). Thus, the illumination with $h\nu$ between $E_{\text{gap}} - \Delta E$ and $E_{\text{gap}}$ plays the most important role in the formation of GaN-porous structures in BSI mode. This model explains very consistently the experimental results obtained in BSI mode in which the pores were etched only at the pore tips in the vertical direction.

In summary, we succeeded in forming GaN-porous structures by using photo-assisted electrochemical etching. The morphology of GaN-porous structures depends on the direction of light illumination. We experimentally demonstrated that the pore depth linearly increased with $Q$ in the BSI mode because the pores were etched only at the pore tips. Our proposed model by considering the Franz-Keldysh effect makes it possible to explain the experimental results consistently. From both the experimental results and theoretical analysis, the BSI mode is powerful for controlling the structural properties of GaN-porous structures such as pore diameter and $d_p$.

Acknowledgments

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References