Minority carrier diffusion length in GaN: Dislocation density and doping concentration dependence

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We investigated the minority carrier diffusion length in p- and n-GaN by performing electron-beam-induced current measurements of GaN p–n junction diodes. Minority electron diffusion length in p-GaN strongly depended on the Mg doping concentration for relatively low dislocation density below \(10^8\) cm\(^{-2}\). It increased from 220 to 950 nm with decreasing Mg doping concentration from \(3 \times 10^{19}\) to \(4 \times 10^{18}\) cm\(^{-3}\). For relatively high dislocation density above \(10^8\) cm\(^{-2}\), it was less than 300 nm and independent of the Mg doping concentration. On the other hand, the minority hole diffusion length in n-GaN was shorter than 250 nm and less affected by the dislocation density and Si doping concentration. We discuss the doping-concentration and dislocation-density dependence of minority carrier diffusion length. © 2005 American Institute of Physics. [DOI: 10.1063/1.1861116]

The recent progress of nitride heterojunction bipolar transistors (HBTs) (Refs. 1–3) will open the door to high-power and high-temperature electronics applications. The minority carrier diffusion length in the base layer of HBTs is one of the key factors determining device characteristics. However, there have been few systematic reports on the doping concentration and dislocation density dependence of minority carrier diffusion length. Electron beam induced current (EBIC) measurements have been carried out to determine the diffusion length normal to the c-axis using Schottky diodes,1–8 but the Mg doping concentration dependence of electron diffusion length or the minority carrier diffusion length parallel to c-axis has not been reported. In addition, EBIC measurements of p–n junction diodes,9–11 the doping concentration and dislocation density dependence of the minority carrier diffusion length has not been previously reported. Considering the minority carrier transport in the base layer of HBTs, it is important to clarify the characteristics of the minority carrier parallel to the c-axis. Therefore, in this paper, we investigate and discuss the doping concentration and dislocation density dependence of minority carrier diffusion length parallel to the c-axis in Si-doped and Mg-doped GaN by EBIC measurements of GaN p–n junction diodes.

GaN p–n junction diode structures were grown by metalorganic vapor phase epitaxy (MOVPE). We used the MOVPE-grown GaN templates on c-face sapphire substrates or bulk GaN substrates. We grew a 1-μm-thick undoped GaN, a 1-μm-thick Si-doped GaN, a 0.7-μm-thick Mg-doped GaN, and a 0.3-μm-thick Mg-doped GaN contact layer. The growth temperature was 1000 °C. The dislocation density \((N_{\text{dis}})\) of the GaN substrates was varied from \(10^6\) to mid-\(10^7\) cm\(^{-2}\) and that of the GaN templates from \(8 \times 10^7\) to \(2 \times 10^9\) cm\(^{-2}\), respectively. The Si doping concentrations for n-GaN were \(4 \times 10^{17}\) and \(4 \times 10^{18}\) cm\(^{-3}\). The Mg doping concentration was also varied from \(4 \times 10^{18}\) to \(3 \times 10^{19}\) cm\(^{-3}\). To make good Ohmic contacts, the Mg doping concentration was fixed at \(3 \times 10^{19}\) cm\(^{-3}\) for the p-type contact layer. After the growth, all samples were annealed at 700 °C in nitrogen to obtain p-type conduction. Separate variable-temperature Hall effect measurements showed that the hole concentration of the Mg-doped GaN at room temperature was around \(1 \times 10^{17}\) cm\(^{-3}\) under these Mg doping concentrations, and that the acceptor concentration was above \(10^{18}\) cm\(^{-3}\), indicating that the depletion layer in p-GaN is 60-nm-thick at most.

The p–n junction diode structures were fabricated using the standard photolithographic technique and electron cyclotron resonance plasma etching. The Ohmic metals for n- and p-GaN were Al/Au and Ni/Au, respectively. All metals were deposited by electron beam evaporation after the surface oxides had been removed by an HCl solution. The samples were cleaved and then mounted on a stage of a scanning electron microscope (SEM). EBIC measurements were carried out with the SEM system equipped with a current amplifier unit (HITACHI S-4100). The electron beam scanned the cleaved surface perpendicular to the plane of the p–n junction. The electron-beam acceleration voltage \(V_{\text{acc}}\) was 10 kV. Since the lateral size of excitation volume was proportional to the \(V_{\text{acc}}^{1.73}\), the low acceleration voltage is preferable to improve the measurement resolution. On the other hand, an electron-beam with a low acceleration voltage will produce electron-hole pairs close to the surface, making the effect of surface recombinaction worse. Cathodoluminescence (CL) measurements have revealed that the CL intensity of GaN band edge emission drastically decreases for acceleration voltages less than 10 kV.13 This indicates that the generated electron-hole pairs were strongly affected by the surface state, that is, the surface recombinaction, for acceleration voltages of less than 10 kV. Therefore, the acceleration voltage was chosen to be 10 kV to achieve high reso-
The minority electron diffusion length in Mg-doped GaN as a function of the dislocation density. The solid curves were obtained by fitting to the experimental data.
time. Therefore, minority holes are less affected by dislocations and impurities, as shown in Fig. 3.

Bandić et al. have reported a simple model for minority carrier lifetime as a function of the dislocation density. They assume that linear dislocations are distributed in a hexagonal “honeycomb-type” array. The minority carrier lifetime, due to recombination at the dislocations ($\tau_{db}$) was obtained by solving the diffusion equation using the parameters of the diffusivity ($D$) and the radius of the dislocation. If we assume that the lifetime without recombination at the dislocations is given by $\tau_0$, then the total minority carrier lifetime is represented as $\tau = \tau_0^{-1} + \tau_{db}^{-1}$. The minority carrier diffusion length $L$ were obtained by the equation $L = \sqrt{D\tau}$ (utilizing the Einstein relationship between $D$ and $\mu$), where $k_B$ is the Boltzmann constant, $T$ is temperature, $\mu$ is the mobility. The mobility depends on the doping concentration due to carrier scattering at the ionized dopants. Therefore, the minority carrier diffusion length was affected by the dislocation density and the doping concentration. The electrical properties of the dislocations has been characterized by scanning Kelvin force microscope. Considering the tip radius of the probe and the tip-induced depletion, the radius of the dislocation core was estimated to be around 10 nm. Therefore, we assumed that the dislocation radius was 10 nm. According to the model described above, we fitted the experimental data. The solid curves in Figs. 2 and 3 show the fitting results, obtained by varying the mobility $\mu$ and the lifetime without scattering at the dislocation $\tau_0$. Table I summarizes the fitting results from EBIC measurements. The minority electron mobilities were calculated to be 139, 113, and 32 cm$^2$/V s for the Mg-doping concentrations of $4 \times 10^{18}$, $1 \times 10^{19}$, and $3 \times 10^{19}$ cm$^{-3}$, respectively. The electron lifetimes without scattering at the dislocation were 2.4, 2.0, and 0.6 ns, respectively. The mobility drastically decreased at the heavy Mg-doping concentration of $3 \times 10^{19}$ cm$^{-3}$, indicating that the electrical properties of Mg-doped GaN were degraded as described before. In Si-doped GaN for the dislocation density below $10^{8}$ cm$^{-2}$, it was reported that the majority electron mobility is mainly limited not by the dislocation density but by the doping concentration. The mobility values decrease with increasing the Si-doping concentration, and they are 170, 100, and 60 cm$^2$/V s for the carrier concentration of $4 \times 10^{18}$, $1 \times 10^{19}$, and $6 \times 10^{19}$ cm$^{-3}$, respectively. These reported majority electron mobility values agree with the minority electron mobility values derived from the EBIC results. On the other hand, the minority hole mobilities were calculated to be 26 and 23 cm$^2$/V s for the Si-doping concentrations of $4 \times 10^{17}$ and $4 \times 10^{18}$, respectively. Both lifetimes without scattering at the dislocation were 0.7–0.8 ns. It was reported that the majority hole mobility values in Mg-doped GaN are 22 and 13 cm$^2$/V s for the hole concentration of $3 \times 10^{17}$ and $1 \times 10^{18}$ cm$^{-3}$ and their Mg-doping concentration of $1.6 \times 10^{19}$ and $8 \times 10^{19}$ cm$^{-3}$, respectively. The reported majority hole mobility values agree with the minority hole mobility values derived from the EBIC results.

This result indicates that the minority hole essentially has the lower mobility and shorter lifetime than those of minority electron. The relatively large hole mobility compared with the majority hole mobility in p-GaN was ascribed to the lower impurity concentration in Si-doped GaN than that in Mg-doped GaN (above $10^{19}$ cm$^{-3}$).

In summary, we have investigated the doping concentration and dislocation density dependence of minority carrier diffusion length parallel to the c-axis by EBIC measurements of GaN p-n junction diodes. The diode structures were grown by MOVPE on GaN with various dislocation densities. Mg and Si doping concentrations were varied to investigate the influence of the impurities on the minority carrier diffusion length. Minority electron diffusion length depended on the Mg doping concentration at relatively low dislocation density and was limited by the dislocation density at relatively high dislocation densities. On the other hand, the hole diffusion length was less affected by the dislocation density and the Si doping concentration, showing that hole diffusion length was essentially shorter than the electron one. A simple model for the minority carrier lifetime including recombination at dislocations gave a good fit to the experimental results.

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<table>
<thead>
<tr>
<th>Sample</th>
<th>Doping concentration (cm$^{-3}$)</th>
<th>Minority carrier</th>
<th>Mobility ($&lt;$cm$^2$/V s)</th>
<th>Lifetime ($\tau_0$) (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-GaN</td>
<td>$4 \times 10^{18}$</td>
<td>electron</td>
<td>139</td>
<td>2.4</td>
</tr>
<tr>
<td>p-GaN</td>
<td>$1 \times 10^{19}$</td>
<td>electron</td>
<td>113</td>
<td>2.0</td>
</tr>
<tr>
<td>p-GaN</td>
<td>$3 \times 10^{19}$</td>
<td>electron</td>
<td>32</td>
<td>0.6</td>
</tr>
<tr>
<td>n-GaN</td>
<td>$4 \times 10^{17}$</td>
<td>hole</td>
<td>26</td>
<td>0.8</td>
</tr>
<tr>
<td>n-GaN</td>
<td>$4 \times 10^{18}$</td>
<td>hole</td>
<td>23</td>
<td>0.7</td>
</tr>
</tbody>
</table>