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]
sion and to decrease the effect of surface recombination. Under these measurement conditions, the resolution of the EBIC measurements was estimated to be better than 50 nm. Figure 1 shows the typical line scan profile obtained by the EBIC measurement. We determined the minority carrier diffusion length $L$ by least-square fitting the obtained EBIC profiles to the simple equation $I = \exp(-x/L)$, where $I$ is the total collected current and $x$ is the relative beam position.\(^{14}\)

Figure 2 shows the minority electron diffusion length in Mg-doped GaN as a function of the dislocation density. Solid squares and open and solid circles correspond to the Mg doping concentration of $4 \times 10^{18}$, $1 \times 10^{19}$, and $3 \times 10^{19}$ cm$^{-3}$, respectively. For relatively low dislocation density below $10^9$ cm$^{-2}$, the minority electron diffusion length depended on the Mg doping concentration and was almost constant irrespective of the dislocation density. The diffusion length drastically increased with decreasing Mg doping concentration. Its values were around 220, 700, and 950 nm for the Mg doping concentration of $3 \times 10^{19}$, $1 \times 10^{19}$, and $4 \times 10^{19}$ cm$^{-3}$, respectively. On the other hand, for relatively high dislocation density above $10^8$ cm$^{-2}$, it is clear that the diffusion length decreased with increasing dislocation density. The diffusion lengths were around 300 nm or less even though the Mg-doping concentration was relatively low, $4 \times 10^{18}$ cm$^{-3}$.

For relatively low dislocation density below $10^8$ cm$^{-2}$, the average period of dislocation was considered to be large enough (>1 \mu m) compared with the minority electron diffusion length. Therefore, the dominant recombination mechanism for minority electrons might not have been the dislocations, but Mg-related impurities. It is expected that a nearest-neighbor associate of an isolated Mg atom in the Ga site and a nitrogen vacancy as well as the acceptor is formed in GaN when Mg is heavily doped above $10^{19}$ cm$^{-3}$ into GaN in MOVPE growth. These associates act as deep donors. The deep donors partially compensate the acceptors, so-called “self-compensation,” resulting in the degradation of the electrical properties of Mg-doped GaN, such as decreased carrier mobility. Therefore, the minority electron diffusion length depended strongly on the Mg doping concentration for relatively low dislocation density below $10^8$ cm$^{-2}$. On the other hand, for relatively high dislocation density above $10^8$ cm$^{-2}$, the minority electron diffusion length did not depend on Mg doping concentration, but on the dislocation density in GaN. The average distance between dislocations is about 220 nm at the dislocation density of $2 \times 10^9$ cm$^{-2}$, where the minority carrier diffusion length was smaller than 300 nm, irrespective of the Mg doping concentration. This means that minority electrons recombinated at dislocations, resulting in the minority electron diffusion length being limited by the dislocation density at relatively high dislocation densities, in particular, above $10^9$ cm$^{-2}$.

In EBIC measurements under low acceleration voltage below 20 kV, almost all reported values of minority electron diffusion length in Mg-doped GaN are less than 300 nm.\(^{6,7,9,10}\) The relatively short electron diffusion length can be ascribed to the heavy Mg doping above $10^{19}$ cm$^{-3}$ or relatively high dislocation density above $10^9$ cm$^{-2}$ in GaN.

Figure 3 shows the minority hole diffusion length in Si-doped GaN as a function of the dislocation density. Solid and open circles correspond to the Si doping concentration of $4 \times 10^{17}$ and $4 \times 10^{18}$ cm$^{-3}$, respectively. The minority hole diffusion length was almost constant for low dislocation density below $10^8$ cm$^{-2}$, and slightly decreased above the dislocation density of $10^9$ cm$^{-2}$. The hole diffusion length also slightly decreased with increasing Si doping concentration. A number of studies have predicted and confirmed negative charges located at the core of edge dislocations.\(^{11,15}\) These dislocations might act as hole traps, which would decrease the hole diffusion length. However, in the present work, the hole diffusion length was almost constant and its value was less than 250 nm even in the low dislocation density and low Si doping concentration. These results indicate that the minority hole diffusion length is essentially shorter than the electron one due to the low hole mobility and/or short life-
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. 16 They assume that linear dislocations are distributed in a hexagonal “honeycomb-type” array. The minority carrier lifetime, due to recombination at the dislocations ($\tau_{\text{dis}}$), 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 by $\tau = \tau_{0}^{-1} + \tau_{\text{dis}}^{-1}$. The minority carrier diffusion length $L$ were obtained by the equation $L = \sqrt{D \tau} = \sqrt{(k_B T \mu / e) \tau}$ (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 have been characterized by scanning Kelvin force microscope. 17 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, the minority hole essentially has the lower mobility and shorter lifetime than those of majority 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 I. Summary of fitting results from EBIC measurements.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Doping concentration (cm$^{-3}$)</th>
<th>Minority carrier</th>
<th>Mobility (cm$^2$/V s)</th>
<th>Lifetime ($\tau_s$) (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>

$1 \times 10^{18}$ 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.