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Investigation of low-temperature cathodoluminescence mechanism of Er-doped GaN thick films by ion implantation

Xiaodan Wang, Yajuan Mo, Xionghui Zeng, Hongmin Mao, Jianfeng Wang, and Ke Xu

Abstract: Er ions are implanted into the GaN thick films grown by hydride vapor phase epitaxy. The implantation energy is 200 keV and the implantation doses are $1 \times 10^{13}$, $1 \times 10^{14}$, $1 \times 10^{15}$, and $5 \times 10^{15}$ atom/cm$^2$, respectively. The effects of the implantation dose and annealing temperature on the GaN band-edge luminescence are investigated. The cathodoluminescence spectra from 82 to 323 K are measured for $1 \times 10^{15}$ atom/cm$^2$ implanted GaN annealed at 1100°C. Luminescence peaks at 356, 362, 376, 390, and 414 nm are observed on the 82 K cathodoluminescence spectrum. When the temperature is increased to 150 K, the intensities of the 356 and 414 nm peaks are nearly unchanged and the 362, 376, and 390 nm peaks disappear. The intensity ratio of 538 nm ($^4H_{15/2} \rightarrow ^4I_{15/2}$) and 559 nm ($^4S_{3/2} \rightarrow ^4I_{15/2}$) is increased with the increase in temperature. We try to shed light on the above interesting phenomena.

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and reached 2 nm when the implantation dose was $1 \times 10^{13}$ Er/cm$^2$. With the increase in the implantation dose, the redshift value increased slowly. The FWHM of the band-edge peak became wider after Er implantation, which indicated that the crystal quality was decreased. Most of the Er ions replaced the lattice sites of the Ga ions. However, it is inevitable that a small quantity of Er ions and Ga ions entered into the interstitial sites because of the collision between Er ions and Ga ions in the process of implantation. Therefore, the periodicity of the crystal lattice became worse after Er implantation.

It is well known that the rare earth ions in the implanted GaN were activated and showed the characteristic emission peaks after being annealed at a certain temperature\textsuperscript{15}. The Er-implanted GaN was annealed and the annealing condition is described in the experiments section. For the $1 \times 10^{15}$ Er/cm$^2$ implanted sample, the Er emission peaks were not observed after the 800°C or 950°C annealing. The strong Er emission peaks were observed after the 1100°C annealing, which indicated that the Er ions were activated adequately.

As shown in Table 2, the position and FWHM of the band-edge peaks of $1 \times 10^{15}$ Er/cm$^2$-implanted GaN before and after annealing are listed. After the 800°C or 950°C annealing, the peak position of the band-edge luminescence did not change, which indicated that most of the Er ions were still in the replacement position of the Ga ions and the bandgap did not change. On the other side, the FWHM decreased about 0.7 nm, which indicated that radiation damage was recovered to some extent. However, as shown in Fig. 2, after the 1100°C annealing the band-edge peak is redshifted from 365 to 367 nm, which indicates that some Er ions are left from the replacement position and combined with the surrounding defects\textsuperscript{13}. The FWHM was decreased from 9.3 to 8.3 nm, which indicated that the radiation damage was partly recovered and the crystal quality became better.

Figure 3 shows the normalized cathodoluminescence spectra of $1 \times 10^{15}$ Er/cm$^2$-implanted GaN after the 1100°C annealing. With the increase in the accelerating voltage, the absolute intensity of the band-edge luminescence and Er-ions luminescence both were increased. At the 5 kV accelerating voltage, the intensity of the Er luminescence at 537 and 558 nm was stronger than that of the band-edge luminescence. At 10 and 15 kV accelerating voltage, the intensity of the Er luminescence at 537 and 558 nm was weaker than that of the band-edge luminescence. At 5, 10, and 15 kV accelerating voltages, the intensity ratios of the 537 nm luminescence to band-edge luminescence were 13.755, 0.673, and 0.12, respectively. It was obvious that the change in the intensity ratio was more than 100 times that when the accelerating voltage was increased from 5 to 15 kV. The reason may be that GaN is a direct bandgap semiconductor and the intensity of the band-edge luminescence increases exponentially with the increase in accelerating voltage. However, under electron excitation, the Er-ion luminescence mechanism is

<table>
<thead>
<tr>
<th>Implantation dose of Er (atom/cm$^2$)</th>
<th>Band-edge peak (nm)</th>
<th>FWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (virgin)</td>
<td>362</td>
<td>8.5</td>
</tr>
<tr>
<td>$1 \times 10^{13}$</td>
<td>364</td>
<td>9.0</td>
</tr>
<tr>
<td>$1 \times 10^{14}$</td>
<td>365</td>
<td>9.3</td>
</tr>
<tr>
<td>$1 \times 10^{15}$</td>
<td>365</td>
<td>9.3</td>
</tr>
<tr>
<td>$5 \times 10^{15}$</td>
<td>365.6</td>
<td>9.8</td>
</tr>
</tbody>
</table>

$^a$The measuring temperature is room temperature.

<table>
<thead>
<tr>
<th>Annealing temperature (°C)</th>
<th>Band-edge peak (nm)</th>
<th>FWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unannealing</td>
<td>365</td>
<td>9.3</td>
</tr>
<tr>
<td>800</td>
<td>365</td>
<td>8.6</td>
</tr>
<tr>
<td>950</td>
<td>365</td>
<td>8.6</td>
</tr>
<tr>
<td>1100</td>
<td>367</td>
<td>8.3</td>
</tr>
</tbody>
</table>

$^a$The measuring temperature is room temperature.

![Fig. 1. Normalized room temperature cathodoluminescence spectra of virgin GaN and $5 \times 10^{15}$ Er/cm$^2$-implanted GaN.](image1)

![Fig. 2. Normalized room temperature cathodoluminescence spectra of $1 \times 10^{15}$ Er/cm$^2$-implanted GaN before and after annealing at 1100°C.](image2)
collision excitation\(^1\). Therefore, the increase in the Er-ion luminescence intensity with the increase in the accelerating voltage is not as fast as the band-edge luminescence. On the other hand, the implantation depth of Er ions was only about 100 nm\(^1\). The penetration depth of electrons in GaN was increased from 90 to 900 nm when the accelerating voltage was increased from 5 to 15 kV\(^1\). Obviously, it is more favorable for band-edge luminescence.

The cathodoluminescence spectra of Er-implanted GaN annealed at 1100°C were measured at a 5 kV accelerating voltage. For 1 × 10\(^{13}\) Er/cm\(^2\)-implanted GaN, Er luminescence was not observed. The cathodoluminescence spectra of 1 × 10\(^{14}\), 1 × 10\(^{15}\), and 5 × 10\(^{15}\) Er/cm\(^2\)-implanted GaN are given in Fig. 4. With the increase in the Er dose, the intensity of the band-edge luminescence was decreased. When the Er dose was increased from 1 × 10\(^{14}\) to 1 × 10\(^{15}\) Er/cm\(^2\), the intensity of the band-edge luminescence was decreased about 15 times. The band-edge luminescence was not even observed in the cathodoluminescence spectra of the 5 × 10\(^{15}\) Er/cm\(^2\)-implanted GaN, which indicated that the radiation damage was not easily recovered. When the Er dose was increased from 1 × 10\(^{14}\) to 1 × 10\(^{15}\) Er/cm\(^2\), the intensity of the Er luminescence was increased about 2 times. When the Er dose was increased from 1 × 10\(^{15}\) to 5 × 10\(^{15}\) Er/cm\(^2\), the intensity of the Er luminescence was decreased about 30%. The decrease of the Er luminescence may be caused by cross relaxation between Er ions\(^\text{[1]}\). We also calculated the Er concentration in the Er-implanted GaN. The implantation depth of Er was about 40 nm at 200 keV energy. It is well known that the number of Ga ions is 4.42 × 10\(^{22}\) in 1 cm\(^3\) volume. Therefore, if the implantation dose was 1 × 10\(^{14}\), 1 × 10\(^{15}\), and 5 × 10\(^{15}\) Er/cm\(^2\), the concentration of Er was 0.056%, 0.56%, and 2.83%, respectively.

As shown in Figs. 5(a) and 5(b), the cathodoluminescence spectra of 1 × 10\(^{15}\) Er/cm\(^2\)-implanted GaN annealed at 1100°C were measured at 82, 150, 223, 293, and 323 K, respectively. The peaks including 356, 362, 376, 390, and 414 nm were observed at the 82 K spectrum. The peak at 356 nm belonged to the free exciton peak\(^\text{[17]}\). The peaks at 362, 376, 390, and 414 nm were related to the Er implantation. The 362 nm peak may belong to the bound exciton peak of the surface defects\(^\text{[18]}\). After ion implantation, the surface roughness of the GaN was increased and the surface defects were produced\(^\text{[19]}\). The peak at 376 nm did not belong to the 2LO peak of free excitation, although the energy difference between the 376 and 356 nm peaks was about 185 meV which was nearly double that of one LO phonon with 92 meV energy. With the increase in temperature, the free exciton peak was shifted to a longer wavelength, but the peak at 376 nm was not moved. Furthermore, the peak at 376 nm was not observed in the cathodoluminescence spectra of the unimplanted GaN. Therefore, the peak at 376 nm most probably

Fig. 3. Normalized room temperature cathodoluminescence spectra of 1 × 10\(^{15}\) Er/cm\(^2\)-implanted GaN after 1100°C annealing, at different accelerating voltages of the scanning electron microscope.

Fig. 4. Room temperature cathodoluminescence spectra of Er-implanted GaN with different doses annealed at 1100°C. The accelerating voltage of the scanning electron microscope is 5 kV.

Fig. 5. Cathodoluminescence spectra of 1 × 10\(^{15}\) Er/cm\(^2\)-implanted GaN annealed at 1100°C. The temperature is from 82 to 323 K and the accelerating voltage of the scanning electron microscope is 5 kV.
belonged to the donor-acceptor luminescence and the donor and acceptor both existed on the surface\textsuperscript{18}. The peak at 390 nm belonged to the bound exciton luminescence, which was related to the point defects\textsuperscript{22}. The peak at 414 nm belonged to deep energy level luminescence and needs to be investigated further. With the increase in temperature from 82 to 150 K, the free exciton luminescence shifted from 356 to 357 nm, and the peaks at 362, 376, and 390 nm disappeared, which indicated that the bound exciton was related to the surface defects and the donor-acceptor pair on the surface, and the bound exciton was related to the point defects being disassembled. On the other hand, with the increase in temperature from 82 to 293 K, the intensity of the band-edge luminescence did not obviously decrease, which may be related to the decomposition of the exciton, and the produced free electron and hole contributed to the band-edge luminescence. The intensity of the peak at 414 nm was nearly unchanged with the increase in temperature, which indicated that this peak was related to the deep energy level. However, when the temperature was increased to 323 K, the intensity of 358 nm peak was even stronger than that of the 559 nm peak. There is a thermal coupling between the $^2$H$_{11/2}$ and $^4$S$_{3/2}$ energy states\textsuperscript{22}. At low temperatures, the $^2$H$_{11/2}$ state is not thermally populated and no luminescence was observed at 538 nm. When the temperature was increased to 150 K, the $^2$H$_{11/2}$ state was thermally populated; therefore, the luminescence at 538 nm was observed. At the same time, the intensity of the 559 nm luminescence was decreased to some extent. On the other hand, when the temperature was increased to 323 K, the intensity of 538 and 559 nm luminescence was not obviously decreased, which indicates that Er-implanted GaN is promising for applications to the high temperature devices.

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References