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Research Article

Research on Degradation of GaN-Based Blue LED Caused by γ Radiation under Low Bias

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GaN multiquantum-well blue light-emitting diodes (LEDs) were radiated with ^{60}Co γ-rays for accumulated doses up to 2.5 Mrad (SiO_2). The radiation-induced current and $1/f$ noise degradations were studied when the devices operate at the low bias voltage. The current increased by 2.31 times, and the $1/f$ noise increased by 275.69 times after a dose of 2.5 Mrad (SiO_2). Based on Hurkx's trap-assisted tunneling model, the degradation of current was explained. γ radiation created defects in the space-charge region of LEDs. These defects as generation-recombination centers lead to the increase in the current. In addition, based on the quantum l/f noise theory, the degradation of $1/f$ noise might be also attributed to these defects, which caused an increase in the Hooge constant and a decrease in the carrier lifetimes. The current and $1/f$ noise degradations can be attributed to the same physical origin. Compared to the current, the $1/f$ noise parameter is more sensitive, so it may be used to evaluate the radiation resistance capability of GaN blue LEDs.

1. Introduction

With the further development of space technology and electronic technology, GaN-based light-emitting diodes (LED) as light source are more and more used in satellites, spacecrafts, missiles, and other equipments. Devices work in space affected unavoidably by the space radiation. There is strong interest in the effects of directly or indirectly ionizing radiation on GaN-based LEDs for space-based applications and radiation monitoring. It is important to study the effect of radiation on the GaN-based LED and to find the physical origin of the degradation mechanisms, having sensitive reliability indicators for its application. The radiation degradation modes in GaN LEDs have been investigated recently. A variety of radiation studies have been carried out [1–7], but there are few studies on the effects of γ radiation on them [8, 9]. Khanna et al. [8] found that forward turn-on voltage was increased slightly, the reverse breakdown voltage was unchanged, and the light output intensity was decreased after GaN-based LEDs were radiated by γ-rays. Li et al. [9] found the redshift of the photoluminescence peak energy of blue GaN-based LEDs exposed to γ-rays.

It is known that low-frequency noise characterization is a sensitive tool to investigate the device quality and to track the changes in the structures. In particular, the $1/f$ noise has been found suitable for study of the physical mechanisms of degradation caused by radiation. It is shown that low-frequency noise characteristic investigation is a sensitive method for explaining quality and reliability problems of optoelectronic devices (laser and LEDs and photodetectors) [10–14]. The low-frequency noise level could be an important indicator of the LED's degradation caused by radiation. Investigation of low-frequency noise characteristics may give valuable information on the physical mechanisms of degradation of LEDs. Nevertheless, there are very few papers where the degradations of $1/f$ noise caused by γ radiation in LEDs are investigated.

In this paper, the degradation mechanism of $1/f$ noise in GaN multiquantum-well blue LEDs caused by γ radiation is studied. Often, a typical *I-V* curve of GaN-based LEDs can be divided into three regions when they operate at the forward bias [11, 15–22],that is, the tunneling current region, the diffusion-recombination current region, and the series resistance region. The mechanism of current and $1/f$

noise in these three parts is different, so the degradation mechanism after γ radiation may be different. For the sake of simplicity, it is only studied the degradation mechanism of current and noise of GaN-based blue LEDs after γ radiation under low voltage bias. It is found that defects in the space-charge region which are caused by γ radiation lead to the degradation of current and noise parameters.

2. Experiment

The experimental devices are GaN multiquantum-well blue LEDs produced by a Taiwan electronics company. GaN epitaxial layers were grown on sapphire substrates by the chemical vapor deposition (MOCVD). From bottom to top, GaN buffer layer, n-GaN layer, n-AlGaN layer, and InGaN quantum-well active region are in turn. The upper part is Mg-doped p-AlGaN layer and p-GaN layer. The devices were radiated with γ ray from a ^{60}Co source at room temperature. The accumulated total dose at each test step was 30 k, 60 k, 200 k, 500 k, 1 M, and 2.5 Mrad (SiO_2). The electrical parameters were measured by an HP4156 semiconductor parameter analyzer. The noise signal was amplified with a PARC113 low noise amplifier and then measured with an XD3020 noise measurement system based on virtual instrument that was described in [23].

3. Results and Discussions

3.1. Results. Because the devices are indeed radiation hard, the parameters of GaN-based blue LEDs did not change significantly when the total radiation dose to the device is much lower than 500 krad (SiO_2). The parameters of the device change obviously, when the total dose of radiation reaches 1 Mrad (SiO_2). Figure 1 shows the *I-U* curve of the low bias voltage. As can be seen from Figure 1, the precision of the measurement is too low (below 1.5 V) to get reliable values. Figure 1 shows that the current increases with the total dose of radiation at the same voltage. The relative change in the current, $\Delta I/I_0$, is plotted versus the total dose in Figure 2 when the bias voltage is 2.23 V, where $\Delta I = I - I_0, I_0$ is the preradiation parameter, and I is the postradiation parameter. Figure 2 shows that $\Delta I/I$ increases with total dose.

Figure 3shows the change in the current noise power spectral density of GaN-based blue LEDs before and after γ radiations when the current equals to 5 μA. As can be seen from Figure 3, the low-frequency noise is the $1/f$ noise for frequencies below 1 kHz. Figure 3 shows that the performance of the $1/f$ noise is degraded significantly with accumulated total dose. The relative change in the current noise power spectral density, $\Delta S_I/S_{I0}$, is plotted versus the total dose in Figure 4 at 20 Hz, where $\Delta S_I = S_I - S_{I0}, S_{I0}$ is the preradiation parameter, and S_I is the postradiation parameter. Figure 4 shows that $\Delta S_I/S_{I0}$ increases with total dose.

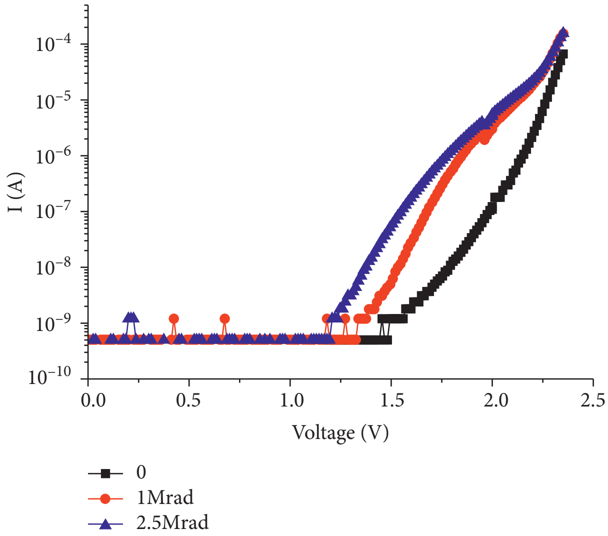

FIGURE 1: *I-U* characteristics before and after radiation at low forward bias.

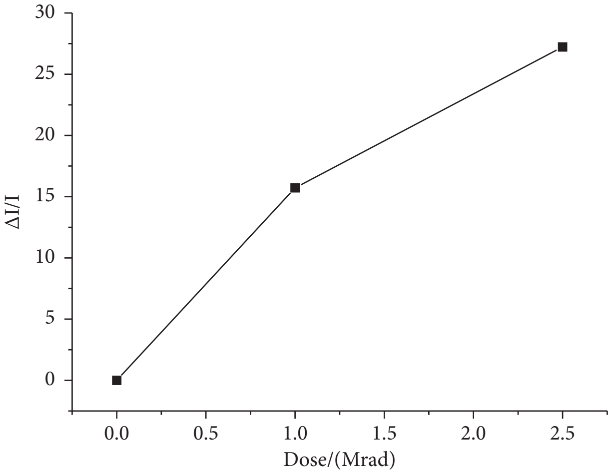

FIGURE 2: Variation of current with total dose ($U = 2.23$ V).

3.2. Discussions. It has been pointed out in many literatures [11, 15–22] that the trap-assisted tunneling current is the main component of the GaN-based LED current when it is biased forward at low voltage (generally less than its turn-on voltage). Recently, it was shown that Hurkx's trap-assisted tunneling model [24] might have been applied to GaN PN junctions [25–27]. Hurkx's model is basically the conventional SRH recombination model with an electric-field-dependent reduction of the carrier lifetimes. The lifetime reduction is due to the fact that at high electric fields, both the carrier capture and emission rates are enhanced by virtue of phonon-assisted tunneling as illustrated in Figure 5. The SRH recombination rate of Hurkx's model can be written as [24, 27]

$$U_{GR} = \frac{np - n_i^2}{\left(\tau_{p0}/\left(1+\Gamma_p\right)\right)\left(n + n_i \exp\left(\left(E_t - E_{\mathrm{Fi}}\right)/kT\right)\right) + \left(\tau_{n0}/\left(1+\Gamma_n\right)\right)\left(p + p_i \exp\left(\left(E_{\mathrm{Fi}} - E_t\right)/kT\right)\right)}, \quad (1)$$

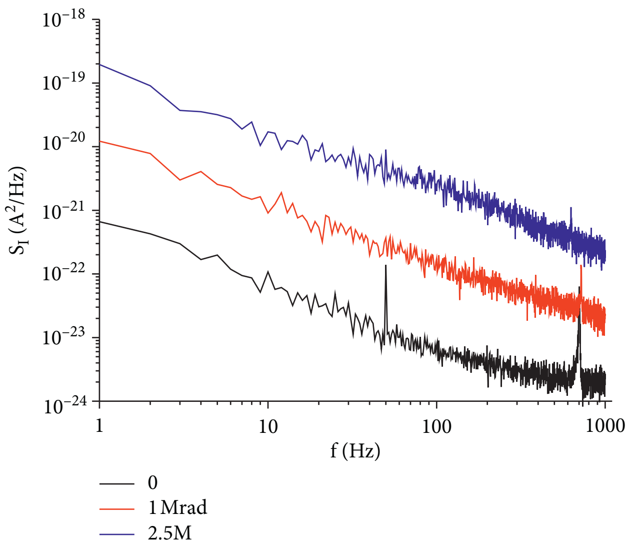

FIGURE 3: Current noise spectral density during radiation for various total doses.

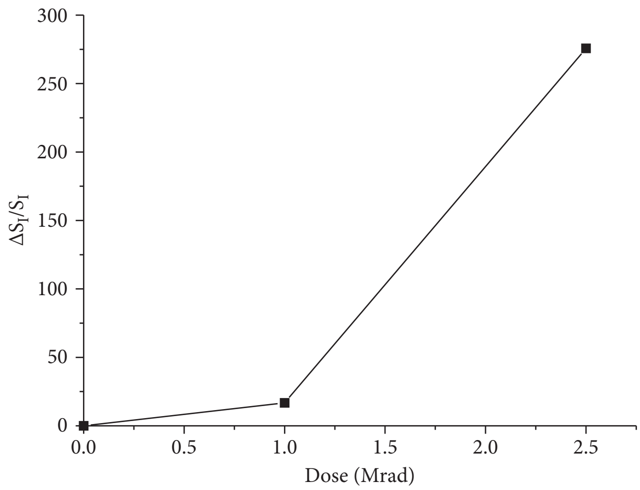

FIGURE 4: Variation of current noise spectral density with total dose ($f = 20$ Hz).

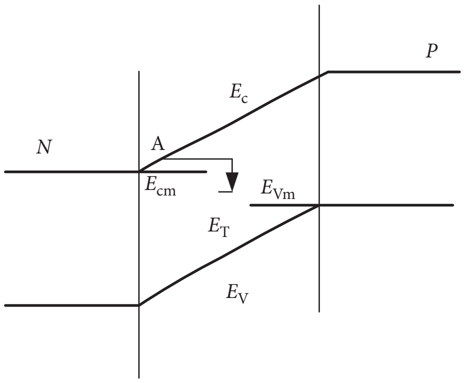

FIGURE 5: Energy band diagram of a depletion layer around a forward-biased junction. The constants E_{cm} and E_{vm} denote the boundary levels, from which the tunneling is possible.

where U_{GR} is the SRH recombination rate, k is the Boltzmann constant, T is the temperature, E_t is the trap level, E_{Fi} is the Fermi level, n is the electron concentration, p is the hole concentration, and n_{i} is the intrinsic carrier concentration.

$\tau_{n0,p0} = (1/N_t c_{n0,p0})$ are the carrier lifetimes of electrons and holes in the absence of an electric field (where N_T is the trap density and c_{n0} and ${}_{p0}$ are the electron and hole capture rates in the absence of an electric field). Γ_n and Γ_p are the field-effect functions, and they are expressed as [24]

$$\Gamma_{n,p} = \frac{D_{n,p}(x)}{kT}\int_0^1 \exp\left(\frac{D_{n,p}(x)}{kT}u - K_{n,p}(x)u^{(3/2)}\right)du, \tag{2}$$

where $K_{n,p}$ is expressed as [24]

$$K_{n,p} = \frac{4\sqrt{2m_{n,p}^{\mathrm{tun}}(x)D_{n,p}^3(x)}}{3q\hbar|F(x)|}, \tag{3}$$

where $m_{n,p}^{\mathrm{tun}}$ are the effective masses of electrons and holes for the trap-assisted tunneling. $F(x)$ is the electrostatic field. ħ is reduced Planck constant. Functions D_n and D_p represent the size of a range of energies, from which the tunneling is possible. For electrons, it reads (compare Figure 5) [24]

$$D_n(x) = \begin{cases} E_c(x) - E_{cm}, & E_t(x) \le E_{cm}, \\ E_c(x) - E_t(x), & E_t(x) > E_{cm}. \end{cases} \tag{4}$$

Similarly, for holes we have [24]

$$D_p(x) = \begin{cases} E_{vm} - E_v(x), & E_t(x) > E_{vm}, \\ E_t(x) - E_v(x), & E_t(x) \le E_{cm}. \end{cases} \tag{5}$$

The trap-assisted tunneling current can be written as

$$I_{GR} = eA\int_0^W U\mathrm{d}x, \tag{6}$$

where A is the area and W is the width of space-charge region.

The behavior of neutral radiation like γ rays passing through semiconductors is fundamentally different than the interaction with charged particles such as protons, electrons, or alpha particles, and the energy loss mechanisms are the photoelectric effect, Compton scattering, and pair production [8, 9]. γ radiation can lead to atomic displacements through secondary effects. These defects may be as generation-recombination centers in the space-charge region. Figure 2 shows that $\Delta I/I$ increases with total dose, and the degradation mechanisms of current can be explained as follows. With the accumulation of total dose, defects increase, which corresponds to increase N_t in formula (1). It leads to the increase of recombination rate. According to formula (6), the current increases also. Therefore, the number of defects increases with the radiation dose and then causes the recombination rate to increase, and the current increases. This can explain the experimental results in Figure 1 very well.

The spectrum for $I = 5\,\mu$A has a $1/f$ spectral shape in the range 1 Hz $< f <$ 1 kHz.

However, no generation-recombination noise is observed. This is because only generation-recombination centers whose energy level in a few kT near the Fermi level can contribute to the generation-recombination noise. $1/f$ noise in semiconductor devices includes surface noise and bulk $1/f$ noise. Since the GaN-based blue LEDs are indeed radiation hard, surface effects are less likely. It may be suggested that the defects introduced by the radiation cause changes in the $1/f$ noises. The reason for the increase in the noise is that the bulk $1/f$ noise changes.

In diodes operating at low temperatures, the current comes about by recombination of holes and electrons in the junction space-charge region. For forward bias, an electron and a hole are sequentially trapped by a recombination center, and for back bias, an electron and a hole are sequentially emitted by such a center. In addition, the emitted electrons and holes are accelerated in the space-charge region, and the electrons and holes coming from the n and p-regions, respectively, are decelerated in the space-charge region before being trapped. All these processes produce (quantum) $1/f$ noise [28, 29]. The time constants fluctuate in a $1/f$ fashion, and this produces the quantum l/f noise. For GaN-based blue LEDs at the low bias, the current comes about by recombination of holes and electrons in the junction space. So, $1/f$ noise of GaN-based blue LEDs is quantum $1/f$ noise. The quantum $1/f$ noise in the bulk space-charge region of PN can be expressed as [28, 29]

$$S_I = \alpha_H \frac{eI_{GR}}{f\left(\tau_n + \tau_p\right)}, \tag{7}$$

where f is the frequency. $1/f$ noise in semiconductor devices is low-frequency noise [30]. $\tau_{n,p}$ is the carrier lifetimes in the existence of the electric field. α_H is an empirical factor, the Hooge parameter, and it can be expressed as [28, 29]

$$\alpha_H = \left(\frac{4a}{3\pi}\right) \frac{2e\left(V_d - V\right) + 3kT}{\left[\left(m_n^*\right)^{(1/2)} + \left(m_p^*\right)^{(1/2)}\right]^2 c^2}, \tag{8}$$

where $a = 1/(137)$ is the fine structure constant and V is the bias voltage, V_d is the diffusion potential of the junction, c is the light speed, m_n^* is the electron effective mass, and m_p^* is the hole effective mass.

The carrier lifetime reduction is due to the fact that at electric fields both the carrier capture and emission rates are enhanced. The carrier lifetimes $\tau_{n,p}$ in the existence of the electric field can be expressed as [27]

$$\tau_{n,p} = \frac{\tau_{n0,p0}}{1 + \Gamma_{n,p}}. \tag{9}$$

Let us calculate the experimental value $a_H/(\tau_n + \tau_p)$ at $I = 5\,\mu$A before radiation. Using (7) and the experiment data, we calculate $a_H/(\tau_n + \tau_p) = 7.5 \times 10^2$. If the carrier lifetime is 10^{-9} s [10, 11], we calculate $a_H = 7.5 \times 10^{-7}$. Using (8) and taking $m_n^* = 0.2$ m and$m_p^* = 1.7$ m (m is the electron effective mass), we calculate $a_H \approx 4.6 \times 10^{-9}$ in theory. The Hooge constant differs by two orders of magnitude in experiment and theory. If Hurkx's model is considered, the carrier lifetime is affected by the field strength, and the lifetime is reduced. If the carrier lifetime is 10^{-10}–10^{-11} s [26], the Hooge constant is little different in experiment and theory.

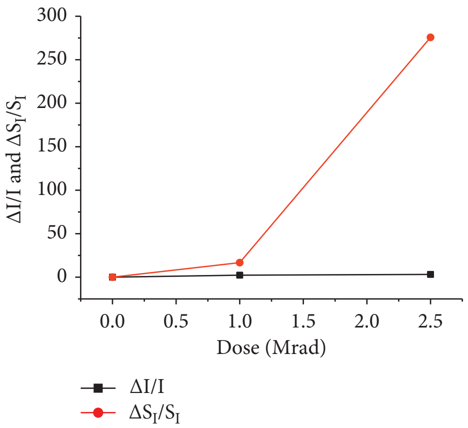

Figure 6: Comparison between variation of current and variation of current noise spectral density.

The degradation mechanisms of $1/f$ noise can be explained as follows. γ radiation can cause defects in the space-charge region of GaN-based blue LEDs. These defects may be generation-recombination centers. When the current is constant, it is shown that the applied voltage decreases with the radiation total dose in Figure 1. According to (8), as the voltage decreases, the Hooge constant increases. At the same time, the electric field F in the space-charge region increases with the decrease of voltage. According to (2) and (3), the field-effect functions $\Gamma_{n,p}$ increase with the electric field F. According to (9), the carrier lifetimes $\tau_{n,p}$ decrease with the increase of $\Gamma_{n,p}$. In addition, the increase of defects caused by γ radiation can reduce carrier lifetime also. So, the Hooge constant α_H increases and the carrier lifetimes $\tau_{n,p}$ decrease after γ radiation when the current I is constant. According to (7), after γ radiation, the conclusion can be drawn that the noise power spectral density S_I increases with the total dose of radiation when the current is constant.

The current and $1/f$ noise degradation of GaN-based blue LEDs attributed to the same physical origins which are the defects caused by γ radiation. So, the $1/f$ noise may be used as a means to evaluate the degradation of GaN-based blue LEDs which is caused by γ radiation. In order to make a comparison, $\Delta I/I_0$ and $\Delta S_I/S_{I0}$ are plotted versus the total dose in Figure 6. It shows that their degradations have a similar trend, and the increase in the $1/f$ noise is more significant than in the current on the same total dose. After a radiation dose up to 2.5 Mrad (SiO_2), $\Delta I/I_0$ is 3.16 and $\Delta S_I/S_{I0}$ is 275.69. It is clear that the $\Delta S_I/S_{I0}$ is more sensitive than $\Delta I/I_0$.

4. Conclusions

The radiations cause defects in the space-charge region of LEDs, which leads to the variance of current and the $1/f$ noise when the devices operate at the low bias voltage. These defects as generation-recombination centers lead to the increase of recombination rate, which leads to the increase of trap-assisted tunneling. In addition, these defects can cause an increase in the Hooge constant and a decrease in the carrier lifetimes, which leads to the degradation of $1/f$ noise. Compared to the electrical parameter, the $1/f$ noise parameter is more sensitive. On the basis of the research, $1/f$ noise measurement may be used as a means to evaluate the radiation resistance capability of GaN-based blue LEDs.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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