Stark Effects Model Used to Highlight Selective Activation of Failure Mechanisms in MQW InGaN/GaN Light-Emitting Diodes

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Abstract—This paper demonstrates the feasibility of creating specific defects in double-heterostructure InGaN/GaN commercial light-emitting diodes by neutron irradiation. Using controlled neutron energy, only one failure mechanism can be activated. Defects are located on the side of the chip and increase the leakage current driven by the well-known Poole–Frenkel effect with \( E_c - E_F = 130 \text{ meV} \) electron trap energy level. The maximal amplitude of the optical spectrum also reveals a drop of about 20% associated with the rise of the leakage current. The Stark effect model highlights the origin of the degradation.

Index Terms—GaN, physics of failure, quantum well, Stark effect.

I. CONTEXT AND OBJECTIVES

N\text{UMEROUS} papers have reported thermal and/or current activation drives to observe more than two different failure mechanisms in optoelectronic devices [1]. In this case, the extrapolation of degradation laws is exclusively empirical. For laser diodes, LEDs, and new technologies, this methodology is not perfectly suitable to extrapolate a lifetime distribution.

One of the possible solutions in actual technologies consists of distinguishing each failure mechanism. However, the main difficulty is activating specific defects in the structure to isolate associated failure mechanisms. Generally, the volume of a single defect is close to 50 Å, which is weaker than the De Broglie wavelength of the material (240 Å for GaAs). In this case, the impact on optical transitions and transport of carriers in the structure must be analyzed using quantum theory [2]. To create such controlled defects in the structure, it is necessary to avoid classical accelerated tests and to propose a new strategy. One solution consists of using particles that have an equivalent wavelength that is close to the defect area with energy higher than the covalent energy. In this context, we are going to demonstrate that controlled neutron energy irradiation is a useful methodology for selective activation of failure mechanisms in packaged double-heterostructure LEDs.

II. EXPERIMENTAL SETUP AND MODEL

A. Technological Description

Fig. 1 shows the typical structure of a 472-nm In\textsubscript{0.2}Ga\textsubscript{0.8}N/GaN multiquantum-well (MQW) commercial LED [6]. The active zone is elaborated with p-\textsubscript{Al0.15}Ga\textsubscript{0.85}N (50 nm) and mixing nanodegradation and quantum theory in relation with carrier transport and optical transitions, quantum degradation laws are investigated. If the material dimension is larger than 100 nm, the degradation laws must be written using a continuous function. For nanocomponents, the degradation laws must be quantified. In the two cases, the quantum theory is well adapted, and the accurate model of degradation can be built for all technology.

This paper highlights the feasibility of the methodology to activate only one kind of defects and adjust this methodology. Double-heterostructure LEDs (DH-LEDs) have been used because all failure mechanisms are well known: defect diffusion in the active zone, leakage current on the side of the chip, and gradual variations of series resistance [3]–[5]. In our case, the leakage current arises from specific neutron energy of about 2.9 MeV and weak flux (1850 cm\textsuperscript{-2} s\textsuperscript{-1}).

The key issue is knowing if neutron irradiation can effectively activate only one failure mechanism exactly corresponding to the arisen failure mechanism (i.e., the leakage current). For conventional technologies (LEDs, laser diodes, etc.), there is no accurate correspondence between the physics of failure and degradation laws. The new methodology presented in this paper can also answer to recent requirements for critical devices: telecom, spatial, or automotive applications.

The knowledge of the lifetime distribution with an upper confidence level is one of the main issues of these applications. In this case, the physical degradation laws are necessary to correctly extrapolate the lifetime distribution.
n-GaN cladding layers [7] and InGaN/GaN (10/40 Å) MQW with indium substitution equal to 0.2 processed by molecular beam epitaxy. Blue light is emitted in 4π steradians around the active zone.

The n-contact is performed using a thin multilayer of Pt (40 nm)/Ti (40 nm)/Au (120 nm) deposited by metal–organic chemical vapor deposition (MOCVD) on GaN N⁺-doped layer (Si/2.5 × 10¹⁸ cm⁻³) [8]. The p-contact consists of a thin film of Ni (10 nm)/Au (10 nm) deposited by MOCVD on a GaN P⁺-doped layer (Mg/2 × 10²⁰ cm⁻³) [7], [9], [10].

Packaged InGaN/GaN DH-LEDs have been irradiated using 2.9-MeV neutrons with 1850 cm⁻² s⁻¹ flux during 12 h with Application Interdisciplinaire des Faisceaux d’Ions en Aquitaine Facilities (Centre d’Etudes Nucléaires de Bordeaux-Gradignan). A specific direction of the samples has been performed to activate the defect on the side of the DH-LED, as shown in Fig. 1.

B. Electrical Model

Electrical measurements are carried out using a Keithley 6430 semiconductor analyzer with a resolution of about 10⁻¹⁷ A and a liquid nitrogen (LN2) cryostat for thermal management. Typical current–voltage LogI(V) characteristics measured at 300 K are shown in Fig. 2.

Electrical measurements are very useful to establish the distribution of currents among each parallel path in a semiconductor device. For a GaN-based material MQW-LED chip, many papers have described a useful simplified electrical circuit or proposed analytic modeling deduced from electrical measurements, where the active zone is generally represented by an ideal heterojunction diode $D_{hj}$ addition with an overall linear resistance (Rs) [11]. The $D_{hj}$ structure corresponds to two different physical phenomena: radiative and nonradiative recombination. For the level of current considered, the diffusion phenomenon can be considered as weak because the cladding layer is used to confine carriers in the MQW zone, as shown in Fig. 3. Then, the electrical model, developed in this paper, does not take into account the diffusion phenomenon.

In our case, the Schottky barrier on the Ni-pGaN contact limits the total current by tunnel effect, and only one mechanism is estimated regarding the analysis of the $I$–$V$ curves shown in Fig. 2.

The following relation gives the equation of the band structure in the quantum well:

$$E^{1}_{ck//} = E_g + \varepsilon_e + \frac{\hbar^2 k_{m}^2}{2m_e}$$

$$E^{1}_{vk//} = \varepsilon_v + \frac{\hbar^2 k_{m}^2}{2m_h}$$

(1)

where $E_g$ is the band gap of GaN, $\varepsilon_e$ is the conduction energy level of the quantum well, $\varepsilon_v$ is the valence energy level of the quantum well, $\hbar$ is the reduced Planck constant, $k_{//}$ is the wave vector in the parallel direction of the quantum well, $m_e$ is the effective mass of the electron in the conduction band, and $m_v$ is the effective mass of the electron in the valence band.

Variations occurring at a weak injection level of the current are directly associated with the direct tunnel current due to the semiconductor–metal contact (Ni/Au–pGaN).

The potential barrier $q\phi_b$ amplitude is evaluated using

$$q\phi_b = q\chi + E_g - q\phi_m = 3.8 \text{ eV}$$

(2)

with $q\chi$ the electronic affinity of GaN (4.1 eV), $E_g$ the band gap of GaN (3.4 eV), and $q\phi_m$ the metal work function of $N_i$ (4.5 eV) [12], [13]. The analytical model of $I$–$V$–$T$...
characteristics is given by simplifying the following coming from the Padovani and Stratton approach [14], [15]:

$$J_{\text{tunnel}} = AT^2 \left( \frac{E_{\infty}}{kT} \right)^2 \frac{\phi_b - V}{\phi_b} \exp \left( \frac{-2(q\phi_b)^{3/2}}{3E_{\infty}\sqrt{q\phi_b - qV}} \right)$$

with $A$ the Richardson constant, $T$ the junction temperature, $k$ the Boltzmann constant, $V$ the bias voltage, and $E_{\infty} = 90$ meV the characteristic energy of doping density, which is given by

$$E_{\infty} = \frac{\hbar}{2} \sqrt{\frac{N_D}{\varepsilon_S m^*}}$$

with $N_D$ the doping density of about $2 \times 10^{26}$ m$^{-3}$, $\varepsilon_S = \varepsilon_{\infty} \cdot \varepsilon_0 = 7.87 \times 10^{-11}$ F·m$^{-1}$ the dielectric constant of GaN, and $m^* = 0.22 \times m_0$ the effective mass of the electron.

The tunnel model leads us to change the representation of the $I$–$V$ curve and transform the $x$- and $y$-axes. This consideration is useful in simplifying the analyses of the physical phenomenon. Then, Fig. 5 shows the plot of $\ln(I/q(\phi_b - V))$ versus $\sqrt{q(\phi_b - V)}$, where the slope is extracted at 54 and given by the following relation:

$$\text{slope} = \frac{2(q\phi_b)^{3/2}}{3E_{\infty}}.$$  

The characteristic energy of doping $E_{\infty}$ is close to 90 meV for a barrier potential equal to 3.8 eV.

For $I$–$V$ at low temperature (100 K), the current presents a different slope, which is mainly caused by the addition of Pt-nGaN contact cleaned in buffered HF [14], [16], [17]. In this case, the combination of thermoionic field emission and thermoionic emission explains the curves $I$–$V$ at 100 K. The equation of the current is given by the relation

$$I = I_{\text{SP}} \left( \exp \left( \frac{qV}{n_F kT} \right) - 1 \right)$$

$$n_F = \frac{E_{\infty}'}{kT} \cot h \left( \frac{E_{\infty}'}{kT} \right).$$

In our case, $E_{\infty}' = 17$ meV for N-doping equal to $2.5 \times 10^{18}$ cm$^{-3}$.

For a high injection level of the current, the Schottky not presented overlapped, and the limitation of the current is only driven by series resistors. In this paper, the series resistance is linear, and the electrical model for this level of the current is given by

$$I_{\text{HIL}} = \frac{V - V_{\text{th}}}{R_s}$$

where $V_{\text{th}}$ is the threshold voltage, and $R_s$ is the total resistance of the structure. The $R_s$ and $V_{\text{th}}$ parameters can be easily extracted from the $I(V)$ curve (Fig. 2). The extracted value gives us the $R_s$ and $V_{\text{th}}$ values versus temperature in Table I.

### C. Spectral Model

The spectral measurements are performed using a Jobin Yvon Triax 320 spectrometer (spectral dispersion of 2.35 nm/mm) with a slit at 50 μm and an LN$_2$ cryostat for temperature regulation.

Theses measurements are used to improve the model of the DH-LED and clarified the physical parameters and failure signatures. The condition of measurement is for a bias current equal to 30 mA for package temperature ranging from 104 to 357 K. To estimate the junction temperature, we based this paper on AlGaAs/GaAs DH-LED assembly in the same package than the MQW InGaN/GaN LED. The thermal resistance of the package is evaluated at 277 K·W$^{-1}$. The handbook value of the GaN and sapphire material gave us the thermal conductivity of $\sigma_{\text{GaN}} = 65.6$ W·m$^{-1}$·K$^{-1}$ and $\sigma_{\text{S}} = 23.1$ W·m$^{-1}$·K$^{-1}$. For the 273.17 K package temperature, the junction temperature is close to 300 K, and we build the model at this condition.

Moreover, great interest of emission spectra measurements has been demonstrated for the characterization and the degradation of LEDs or laser diodes. Several papers have reported results on emission spectra changing, wavelength shift, and apparition of new peaks after aging tests [18], [19]. These changes in electroluminescence characteristics are related to degradation in the active region.

The luminescence under the quantum-well gap level (2.683 eV at 300 K) is relative to the confined Stark effect explained by the wave function of carriers specifically expressed by Airy function $Ai(z)$ solutions in the following [20]:

$$\frac{d^2 Ai(z)}{dz^2} - z Ai(z) = 0$$

where $z$ is the perpendicular direction of epitaxy planes.

The main cause of the Stark effect is the electrical field applied on the MQW that modified the slope of the bands (Fig. 6) [21], [22].

### Table I

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Threshold voltage $V_{\text{th}}$ (V)</th>
<th>Resistance $R_s$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>104</td>
<td>4.118</td>
<td>11.263</td>
</tr>
<tr>
<td>185</td>
<td>3.287</td>
<td>12.91</td>
</tr>
<tr>
<td>273.15</td>
<td>3.0039</td>
<td>12.773</td>
</tr>
<tr>
<td>301.24</td>
<td>2.9253</td>
<td>13.162</td>
</tr>
<tr>
<td>357</td>
<td>2.777</td>
<td>13.723</td>
</tr>
</tbody>
</table>
For radiative recombination, the Airy function is exponential, as the following relation shows:

$$ Ai(z) \approx \frac{1}{2 \sqrt{\pi z}} \exp \left( -\frac{2}{3} \sqrt{\frac{3}{z}} \right). \quad (9) $$

The spontaneous emission relative to the Stark effect can be expressed by

$$ R_\Delta(\xi) = r_0 \sqrt{\beta \pi} \left( \frac{d Ai(-\xi)}{dz} \right)^2 + \xi Ai^2(-\xi) $$

$$ \beta = \left( \frac{2m_e}{\hbar^2 q^2 F^2} \right)^{1/3}; \quad \xi = \frac{h\nu - E_g}{\beta} \quad (10) $$

where $F$ is the electrical field applied on the active zone. The electrical field due to the bias voltage is about $1.5 \text{ MV/cm}$. To fit the analytical curve with the experimental one, an additional electrical field, due to the internal field of the Wurzite structure, of about $1.2 \text{ MV/cm}$ must be added to the bias voltage contribution. It has been demonstrated that the InGaN/GaN structure has an internal electrical field close to $1 \text{ MV/cm}$ and due to the piezoelectric effect in the heterostructure [23], [24]. The Stark effect allows us to identify the internal electric field due to the piezoelectric effect in the MQW-LED.

Considering carrier recombination in the MQW-LED, classical spontaneous recombination probability $R_{\text{sp}}(E)$ is completed by stimulated emission represented by optical gain $\gamma(h\nu)$ [25], [26]. Physical modeling proposed by Rosencher and experimentally observed by Ramoo is built from the theoretical expression of spontaneous emission $R_{\text{sp}}(E)$ with modification taking into account the nonparabolic characteristic of the band structure that develops in relation (1). Equation (11) is given by the specific analytical calculus of the spontaneous emission rate based on the Einstein theory, i.e.,

$$ R_{\text{sp}}(E) = K_{\text{sp}}(E - E_g)^{1/m} \exp \left( -\frac{E - E_g}{kT} \right) $$

$$ K_{\text{sp}} = \left( \frac{2m_e}{\pi \hbar^2 \tau_R} \right)^{1+1/m} \exp \left( -\frac{\Delta E_F - E_g}{kT} \right) \quad (11) $$

where $E_g$ is the gap energy level of the quantum well, $m_e$ is the effective mass of the electron, $m$ is the coefficient traducing the nonparabolic characteristic of the band structure ($m = 1.2$), $\tau_R$ is the radiative lifetime, $E$ is the photon energy, $kT$ is the phonon energy, and $\Delta E_F$ is the difference between conduction and valence Fermi levels ($\Delta E_F = 2.969 \text{ eV}$).

The $\Delta E_F$ parameter is described as follows:

$$ \Delta E_F = E_{\gamma c} - E_{\gamma v} $$

$$ E_{\gamma c} = E_{\text{InGaN}} + \varepsilon_c + kT \ln \left( \exp \left[ \frac{J_{\text{tot}} \pi \hbar^2}{q m_e kT} \right] - 1 \right) $$

$$ E_{\gamma v} = \varepsilon_v - kT \ln \left( \exp \left[ \frac{J_{\text{tot}} \pi \hbar^2}{q m_e kT} \right] - 1 \right) \quad (12) $$

where $J$ is the current density of the component, $\tau_{\text{tot}}$ is the total carrier lifetime, $m_v$ is the effective mass of holes, $m_e$ is the electron effective mass, $\varepsilon_v$ is the energy level of quantum wells in the valence band, and $\varepsilon_c$ is the energy level of quantum wells in the conduction band.

The part of spontaneous emission is amplified by stimulated radiation in the MQW-LED. The optical gain is considered with the following for a single energy level in the quantum well, i.e.,

$$ \gamma(h\nu) = \alpha_{2d} \left[ f_c^1(h\nu) - f_c^\alpha(h\nu) \right] \theta \left( h\nu - E_g - \varepsilon_c - |\varepsilon_v| \right) \quad (13) $$

where $f_c^1(h\nu)$ is the conduction band Fermi function, $f_c^\alpha(h\nu)$ is the valence band Fermi function, and $\alpha_{2d}$ is the absorption coefficient of the quantum well.

Arbitrary unit experimental and simulated $L(E)$ and $\gamma(h\nu)$ curves are reported in Fig. 7. At this level of energy, only spontaneous emission is observed, and (11) allows us to extract the active zone temperature $T_j$. We choose to operate at $T_j = 300 \text{ K}$ to compare the result obtained with those of electrical measurements.

The model is well established for all the energy of spectral measurement physical parameters extracted from the fitted model, which are sufficient for failure mechanism analyses.

III. RESULTS AND DISCUSSION

After controlled neutron irradiation, the leakage current (increasing about 3 decades at $300 \text{ K}$) appears at a low bias in the current–voltage curves. The electrical failure signature obtained versus temperature is shown in Fig. 8.

The temperature dependence of the $I(V)$ curve is well adapted to extract a physical phenomenon explaining the leakage current drift: the Poole–Frenkel phenomenon. This kind of
The conduction theory based on the diffusion of the carrier on the defect drives us to consider (14) to simulate the $I(V)$ behavior, i.e.,

$$J_{PF} = \frac{q\mu_p}{2} \left( \frac{N_cN_d}{2} \right)^{1/2} \frac{F}{2kT} \exp\left( -\frac{\Phi_{PF}F^{1/2}}{2k} \right)$$

where $\mu_p$ is the carrier mobility in the active zone, $N_c$ is the effective density of the state in the conduction band, $N_d$ is the defect density, $\Phi_{PF}$ is the Poole–Frenkel barrier, and $\beta_{PF}$ is the Poole–Frenkel coefficient.

The model is based on the well-known relations adapted for the homogeneous current density $I = J \cdot S$ and $V = q \cdot F$, where $S$ is the area of the active zone.

This model is based on the quantum theory, which explains the local disturbance in the structure [27]. In this model, the density of defects is weak (less than $10^{10}$ cm$^{-3}$), with no recovering wave function between two defects [28]. The conduction mechanism is the thermoelectronic emission of the carrier between the defect center and the conduction band. The potential barrier is defined by $\Phi_{PF} = E_c - E_T = 130$ meV in our case.

The number of parameters used in the model given in (14) leads us to consider a different representation of electrical characteristics. In this case, we can isolate the different parameters to estimate their values.

The first parameter estimated with this method is the Poole–Frenkel coefficient using $J/F = f(\sqrt{F})$ curves versus temperature presented in Fig. 10. $\beta_{PF}$ is extracted from the slope of the curves (slope = $\beta_{PF}/2kT$), and defect densities are extrapolated to the amplitude of $I/V$ for $V = 0$ V.

The number of defects is very weak and close to $10^8$ cm$^{-3}$. The hypothesis concerning the density of defect is clearly respected, and the model of the current transport is validated.

The second parameter $\Phi_{PF}$ is extracted using the slope of the curves exposed in Fig. 11 [slope = $-\frac{\Phi_{PF}}{2k} + (\beta_{PF}/2k)]$. The slope is linearly dependent with $\sqrt{F}$, and we determine the value of $\Phi_{PF} = 130$ meV.

The spectral failure signature is plotted in Fig. 12(a) and shows the decrease in the optical spectrum intensity of about 20%. The extraction of physical parameters gives us the same value excepted for $\Delta E_F$ and $F$.

After neutron irradiation, $\Delta E_F$ is close to 2.8895 eV for $I_{bias} = 30$ mA. With (12), we find that the equivalent current in the structure is close to 23 mA. This information conducts us to consider that 7 mA of the current is lost outside the active zone. To confirm this hypothesis, we have analyzed the Stark coefficient. The amplitude of the voltage is the same, and the $\beta$ coefficient (10) is the same. Fig. 12(b) shows that the slope of the curve did not change before and after neutron irradiation.
This observation is clearly in accordance with the constant value of $\beta$.

In this case, the defect responsible for the degradation of the MQW-LED is located on the side of the chip outside the active zone.

The first analysis of electrical and optical signatures indicates that the active zone is not affected because, principally, $\alpha_{2d}$ and $\tau_T$ coefficients did not change before and after neutron irradiation. The semiconductor/coating interface might be affected. The transport of carriers is driven by the diffusion phenomenon related to the defects located in this interface semiconductor/package [6]. A Poole–Frenkel model has been used to explain the leakage current induced by electron trapping by an energy level of 130 meV. The strong interest of temperature tests, the phonon activated by temperature breaks the hydrogen link of plastic coating and creates the energy-level traps. For the temperature tests, the phonon activated by temperature breaks the same link; however, it is impossible to localize this kind of effect. The temperature is the global perturbation of the device, whereas the neutron irradiation corresponds to specific interaction driven by energy amplitude and sample direction.

This first experience shows the feasibility of activating a single failure mechanism using the specific energy of neutrons. In our case, the leakage current is related to the degradation of the side of the chip. The degradation of interface chip/coating is generally activated by temperature, but diffusion of defects is also observed for these basic tests [29], [30]. In our case, 2.9 MeV of neutrons breaks the hydrogen link of plastic coating with a semiconductor and creates the energy-level traps. For the temperature tests, the phonon activated by temperature breaks the same link; however, it is impossible to localize this kind of effect. The temperature is the global perturbation of the device, whereas the neutron irradiation corresponds to specific interaction driven by energy amplitude and sample direction.

In this paper, the feasibility to generate only one failure mechanism in a conventional DH-LED has been demonstrated by setting the basis of reliability investigation. In this case, we can establish a close relation between failure mechanisms and failure signatures. The main interest of our methodology is the activation of only one failure mechanism that is typically found for a specific technology using neutron irradiation.

### References
