CHARACTERIZATION OF HOT-ELECTRON EFFECTS ON FLICKER NOISE IN III-V NITRIDE BASED HETEROJUNCTIONS

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ABSTRACT

We report experiments on hot-electron stressing in commercial III-V nitride based heterojunction light-emitting diodes. Stressing currents ranging from 100 mA to 200 mA were used. Degradations in the device properties were investigated through detailed studies of the I-V characteristics, electroluminescence, Deep-Level Transient Fourier Spectroscopy and flicker noise. Our experimental data demonstrated significant distortions in the I-V characteristics. The room temperature electroluminescence of the devices exhibited 25% decrement in the peak emission intensity. Concentration of the deep-levels was examined by measuring the Deep-Level Transient Fourier Spectroscopy, which indicated an increase in the density of deep-traps from 2.7×10^{13} cm^{-3} to 4.21×10^{13} cm^{-3} at $E_1 = E_C - 1.1$eV. The result is consistent with our study of *1/f* noise, which exhibited up to three orders of magnitude increase in the voltage noise power spectra. Our experiments show large increase in both the interface traps and deep-levels resulted from hot-carrier stressing.

INTRODUCTION

The III-V nitrides family, AlN, GaN, InN, and their ternary alloys are all wide direct bandgap semiconductors. They have significant applications in optoelectronics, particularly in the blue to UV range [1-4]. Since there are no native substrates for epitaxial growth of nitride films, (0001) sapphire is the most widely used substrate because of its hexagonal structure and high temperature stability. The large stress due to lattice mismatch between nitride film and sapphire substrate leads to defective film growth, such as microtwins, (0001) stacking faults and deep-level defects. Moreover, interface traps in the heterostructure may significantly affect the performance of the devices. In this paper, we report degradations of the optical and electrical properties in III-V nitride heterojunctions due to high current stressing and its effects on deep-levels and low-frequency excess noise.

Deep-levels at the bulk regions of the devices are examined by Deep-Level Transient Fourier Spectroscopy (DLTFS). The technique was first described by Weiss and Kassing [5], which is a DLTS utilizing Fourier analysis of the capacitance transient collected as a function of temperature. It has significant advantages over both rate window and lock-in amplifier type systems in terms of sensitivity and energy resolution.

Flicker noise in semiconductor devices is highly sensitive to the presence of crystalline defects [6-10], however, it has not yet received the necessary attention in III-V nitride based devices. Experiments by the author on Random Telegraph Noise in GaAs/AlGaAs double barrier heterostructures showed that the low-frequency noise arise from the thermal activation of carriers to traps located at the heterointerface [8]. Flicker noise measurement can, therefore, be utilized as a sensitive tool for characterizing defect states in semiconductors [9,10]. The variation of the noise on high current stressing will, therefore, reflect the changes of the heterointerface traps resulting from hot-electron degradation. These traps are located at the barrier layers and usually at energy levels beyond the range that can be detected by conventional techniques such as DLTS. By detailed examination of both the DLTFS and *1/f* noise of the devices we provide a more complete picture on hot-electron degradation of the devices.

EXPERIMENT

Systematic study on hot-electron degradation in AlGaN/InGaN heterojunctions was conducted on commercial blue Light Emitting Diodes (LEDs) manufactured by Nichia Chemical Industries Ltd. by means of high current stressing with a dc current of 200 mA for 40 minutes. Detailed measurement of I-V characteristics over a wide temperature range, room temperature electroluminescence (EL), DLTFS and flicker noise were carried out before and after the current stress to examine the degradations of the optoelectronic properties of the LEDs.

DLTFS measurements were conducted from 77 K to 500 K using Bio-Rad DL8000, a high sensitivity, $10^{-7}(N_D - N_A) < N_{DL} < 10^{-5}(N_D - N_A)$, system equipped with a 1 MHz Boonton bridge. To obtain the DLTFS, the devices were periodically pulsed to 1 V for trap filling followed by the application of a -5.0 V reverse bias, V_R, to the device. A transient recorder was used to sample data points from the capacitance transient, $C(t)$, resulting from discharging the deep-levels. Discrete Fourier coefficients of $C(t)$ were computed, providing the basis for direct evaluation of the time constant and the amplitude for each transient. Analysis by Weiss and Kassing [5] showed that the time constant t_{DL} is related to the Fourier coefficient given by $t_{DL} = T_w b_n / 2pna_n$, where a_n and b_n are the n^{th} order cosine and sine coefficients of the capacitance transience, $C(t)$, and T_w is the period.

The low-frequency noise of the devices, which were biased with a passive current source at 0.7 mA, was characterized from room temperature down to about 120 K. Detailed experimental set-up was described in previous publications [6,8]. The current noise power spectral density is shown to be

$$S_I(f) = 4(\Delta I_o)^2 \int\int\int N_T(E) \frac{t}{1 + 4p^2 f^2 t^2} dxdydzdE, \tag{1}$$

in which $N_T(E)$ is the interface trap density, ΔI_0 is the current fluctuation due to the capture of one single carrier and t is the fluctuation time constant. Low-frequency noise in GaAs/A1GaAs based semiconductor heterostructures was shown to originate from trapping and detrapping of carriers by localized states. The capture of charged carriers may arise either from a tunneling or thermally activated process. For flicker noise originating from the thermal activation of carriers to localized states in the energy barrier, the fluctuation time constant, t, is a thermally activated parameter given by $t = t_0 \exp(E / k_B T)$, where t_0 is typically taken to be the inverse phonon frequency of the order 10^{-14} second, and E is the activation energy. This stipulates a strong temperature dependence for t. The Lorentzian, $t/(1 + \omega^2 t^2)$, in Eq. 1 is a sharply peaked function of the activation energy at $E_p = - k_B T \, 1n(t_0 \omega)$. Thus, the properties of flicker noise are highly sensitive to the concentration and energy distribution of the traps at around E_p.

RESULTS

Typical I-V curve for the pre-stressed device is shown in curve A of Fig. 1. The data shows that the I-V characteristics of the device are well behaved with very low leakage current. However, there was a significant increase in the leakage current of the same device as a result of hot-electron stressing, as shown in curve B of Fig. 1. Previous study of Random Telegraph Noise in GaAs/A1GaAs based heterojunctions by the author clearly showed that localized states in the tunneling barrier are responsible for both the *1/f* noise and trap assisted tunneling. Therefore such large increase in the leakage current indicates a corresponding large increase in the trap concentration in the barrier region of the heterojunction.

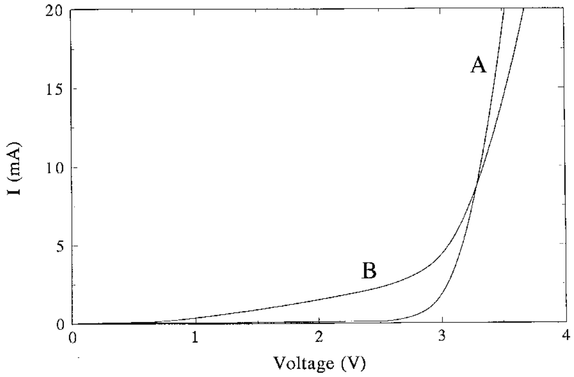

Fig. 1: Typical room temperature I-V characteristics of the LED before hot-electron stressing (curve A) and after 40 minutes of hot-electron stressing at 100 mA (curve B).

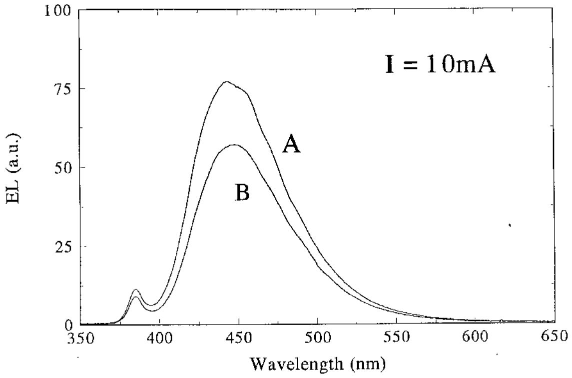

Fig. 2: Typical room temperature electroluminescence of the device before hot-electron stressing (curve A) and after 40 minutes of hot-electron stressing at 100 mA (curve B).

Typical room temperature EL characteristics are shown in curve A of Fig. 2, which indicates a dominant peak at about 450 nm and a much smaller peak at about 380 nm. After hot-electron stressing we observe significant deviations of the EL from its pre-stressed values, which demonstrated approximately 25% decrease in intensity at its peak emission wavelength at approximately 450 nm. The lowering in EL suggests that hot-electron stressing led to substantial increase in non-radiative recombination centers in the heterostructures. It is noteworthy that we do not observe any new peaks in the EL due to the stressing experiment.

The DLTFS results, as shown in Fig. 3, show a significant increase in the magnitude after current stressing which is attributed to the increase in the concentration of deep levels. The results on the optoelectronic properties of the devices are compared to the experimental data from DLTFS measurements. The first sine coefficient, b_1, of $C(t)$ is shown to be comparable to the conventional DLTS signal with a time constant of about 64 ms [5]. Using a reverse bias of V_R = –5.0 V, the experimental data exhibited a deep-level trap at $E_1 = E_C - 1.1$ eV with a concentration of 2.70×10^{13} cm^{-3} and a capture cross section of 5×10^{-14} cm^2. We also observed a shift towards lower temperature for the DLTFS signal peak using a, bias voltage $V_R = -6$ V. This is indicative of field-enhanced electron emission showing that the deep-levels were electron states. Hot-electron stressing led to increase in the concentration of deep-levels. The DLTFS signal is shown in curve B of Fig. 3. From the data we found that $E_1 = E_C - 1.1$ eV with a concentration of 4.21×10^{13} cm^{-3} and a capture cross section of 5×10^{-14} cm^2. It is interesting to note that the DLTFS signal in Fig. 3 shows that a second deep-trap may exist at a shallower energy level. However, due to limited temperature range that can be accomplished by our system, we did not observe its peak in the DLTFS signal and therefore unable to evaluate this level accurately.

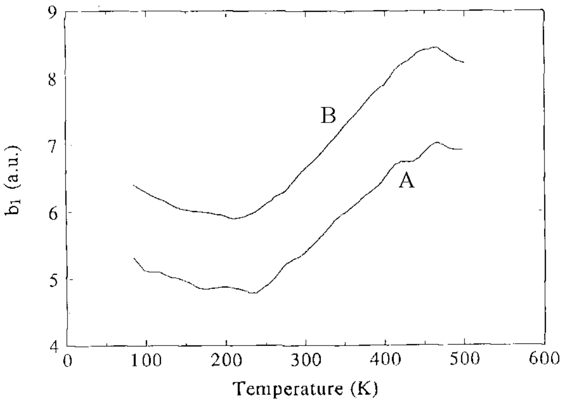

Fig. 3: DLTFS signal for the pre-stressed device (curve A) and the stressed device (curve B).

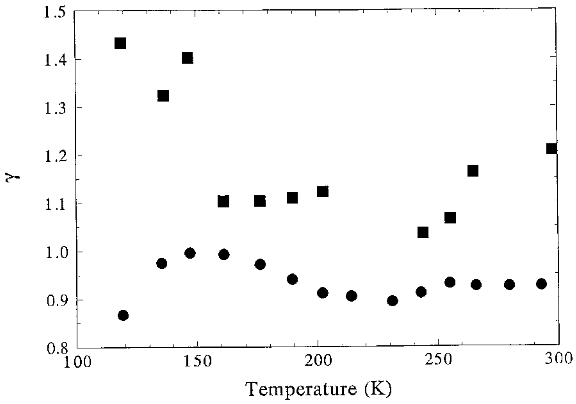

Fig. 4: The frequency exponent, γ, of $S_V(f)$ versus device temperature before current stressing (solid circles) and after stressing (solid squares).

The noise power spectral densities were found to be proportional to $1/f^{\gamma}$ where γ varied between 0.85 to 1 as the device temperature was lowered from room temperature to 120 K. The results are indicated by solid circles in Fig. 4. After hot-electron stressing, we observe a dramatic change in the frequency exponent, γ. This is sufficient proof that the observed *1/f* noise originated from a thermally activated process. There is no alternative model that can adequately explain the systematic temperature dependence of γ.

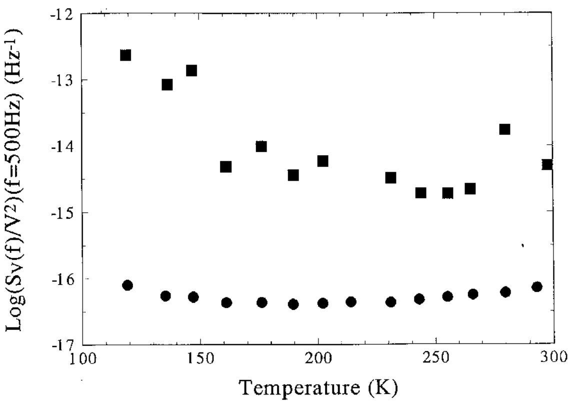

Fig. 5: The normalized voltage noise power spectra, $S_V(f)/V^2$, at f = 500 Hz versus device temperature before stressing (solid circles) and after stressing (solid squares).

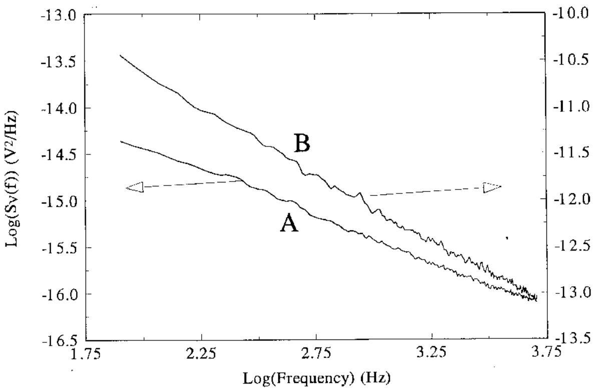

Fig. 6: Typical voltage noise power spectra, $S_V(f)$, for the pre-stressed device (curve A) and the stressed device (curve B) measured with a biasing current of 0.7 mA.

The voltage noise power spectra were found to be sensitive to temperature change as well. Typical results for the normalized noise power spectra, $S_V(f)/V^2$, at f =500 Hz, are represented by solid circles in Fig. 5. It is found that $S_V(f)/V^2$ decreased from 7×10^{-17} Hz^{-1} to about 4×10^{-17} Hz^{-1} at 200 K. Further lowering in the device temperature led to an increase in $S_V(f)/V^2$ to about 8×10^{-17} Hz^{-1} at 120 K. An increase by as much as 3 orders of magnitude in the noise power spectra is observed over the temperature range in which the experiment was conducted.

Typical voltage noise power spectra before and after the hot-electron stressing experiment are shown in curves A and B of Fig. 6 respectively. The voltage noise power spectra, were measured at T = 147 K with the biasing current set at 0.7 mA. Such drastic increase in the noise magnitude subsequent to hot-electron injection stipulates that the noise capture and emission of carriers by traps at the heterojunctions. Unfortunately, without detailed information of the device calculation of the exact values of the trap density would be impossible.

CONCLUSION

In conclusion, we have conducted systematic characterizations of hot-electron stressing on the properties of III-V nitride LEDs. The stressing experiment is seen to cause significant degradations in both the I-V and electroluminescence of the devices. Our experimental data demonstrate that high dc current stressing leads to significant increase in the concentration of deep states at $E_1 = E_C - 1.l$ eV. Within the range of our experimental conditions we do not observe the generation of new deep states at different energy levels. Flicker noise from the devices was studied in detail from room temperature to 120 K. The results showed that the noise originated from the thermal activation of carriers to localized states in the junction, leading to the modulation of the device conductance. Hot-electron stressing result in significant generation of heterointerface traps in the heterostructures leading to three orders of magnitude increase in the voltage noise power spectra. Both the deep-levels and the hetcrointerface traps are believed to play significant roles in the degradation of the optoelectronic properties of the devices.

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