Operation-induced short-term degradation mechanisms of 275-nm-band AlGaN-based deep-ultraviolet light-emitting diodes fabricated on a sapphire substrate

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The short-term degradation mechanisms of 275-nm-band AlGaN multiple quantum well (QW) deep-ultraviolet light-emitting diodes fabricated on a (0001) sapphire substrate were investigated under hard operation conditions with the current density of 66 A/cm^2 and the junction temperature of 105 °C. The optical output power (P_o) decreased by about 20 % within the operating time (t_{op}) less than 102 h and then gradually decreased to about 60 % by 484 h, as shown in Fig. 1. For elucidating the cause for the initial degradation (t_{op} < 102 h), complementary electrical, time-resolved photoluminescence (TRPL), and impurity characterizations were carried out making a connection with the energy band profiles.

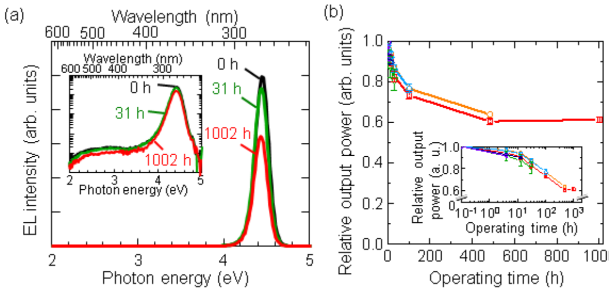

Figure 1 (a) Room-temperature EL spectra of the 275-nm-band $Al_xGa_{1-x}N$ QW LEDs before and after the operation (t_{op} = 0, 31, and 1002 h). (b) Relative optical output power of the LEDs as a function of t_{op}.

The initial degradation was accompanied by the increases in both the forward current (I_F) below the turn-on voltage (V_D) and reverse leakage current (I_R). These results are consistent with those reported previously [1-5]. Because the weak-excitation room-temperature PL lifetime for the near-band-edge emission (τ_{PL}^{NBE}) using the QW-selective TRPL showed only slight change by the operation at least until 1002 h, the initial degradation is attributed essentially to the decrease in carrier injection efficiency ($\eta_{\text{injection}}$). From the correlation between the energy band profiles and H concentration profiles before and after the operation, the $\eta_{\text{injection}}$ reduction is ascribed to be due to depassivation of initially H-passivated preexisting nonradiative recombination centers (NRCs) in a Mg-doped p-type $Al_{0.85}Ga_{0.15}N$ electron blocking layer (EBL) caused by certain breaking of H bonds and the electric field induced drift of H^+. According to our database on the species of vacancy-type defects acting as NRCs in AlN [6] and GaN [7], vacancy clusters comprised of a cation vacancy (V_{III}) and nitrogen vacancies (V_N), such as $V_{III}(V_N)_{2\sim4}$, are the most suspicious origins of the NRCs in the Mg-doped p-type AlGaN layers [8].

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[1] C. Moe *et al.*, Appl. Phys. Lett. **96**, 213512 (2010). [2] M. Meneghini *et al.*, Microelectron. Reliab. **50**, 1538 (2010). [3] A. Pinos *et al.*, J. Appl. Phys. **109**, 103108 (2011). [4] F. Piva *et al.*, Photonics Res. **8**, 1786 (2020). [5] J. Glaab *et al.*, J. Appl. Phys. **131**,014501 (2022). [6] A. Uedono *et al.*, J. Appl. Phys. **105**, 054501 (2009); J. Appl. Phys. **128**, 085704 (2020). [7] S. F. Chichibu *et al*, Appl. Phys. Lett. **86**, 021914 (2005); J. Appl. Phys. **123**, 161413 (2018); Appl. Phys. Lett. **112**, 211901 (2018). [8] S. F. Chichibu *et al*, Appl. Phys. Lett. **122**, 201105 (2023). Author for correspondence: chichibulab@yahoo.co.jp

Supplementary Information

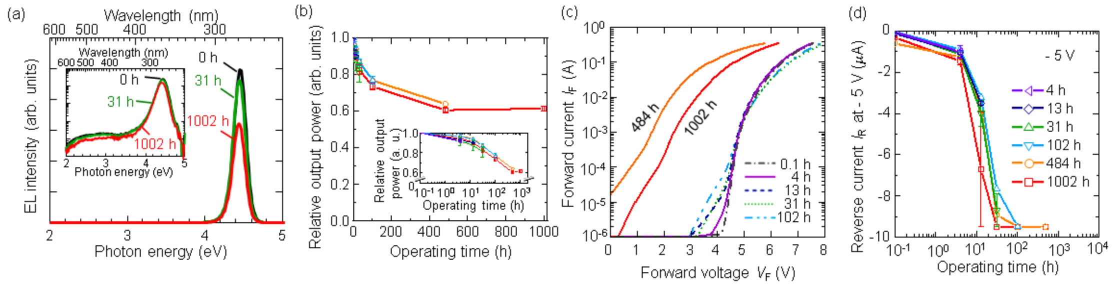

Fig. S1: (a) Room-temperature EL spectra of the 275-nm-band $Al_xGa_{1-x}N$ MQW LEDs before and after the operation (t_{op} = 0, 31, and 1002 h). (b) Relative optical output power of the LEDs as a function of t_{op}. (c) Forward current (I_F) - voltage (V_F) characteristics and (d) reverse current (I_R) at V= - 5 V for the LEDs as a function of t_{op}.

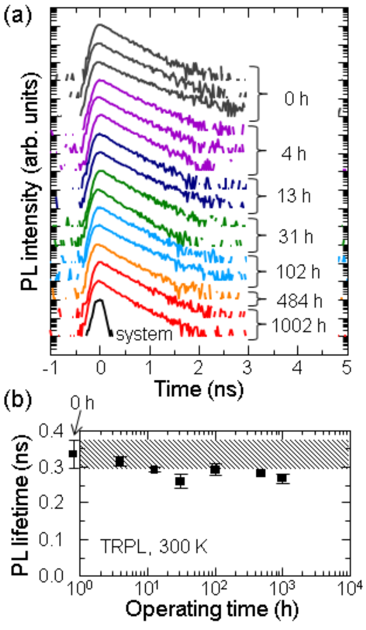

Fig. S2: (a) Room-temperature NBE PL intensities for a series of LED chips as functions of time after excitation (x-axis) and t_{op}. (b) Room-temperature τ_{PL}^{NBE} of the LED chips as a function of t_{op}. Shaded zone indicates τ_{PL}^{NBE} for a series of pristine LED chips showing little but distinguishable individual differences.

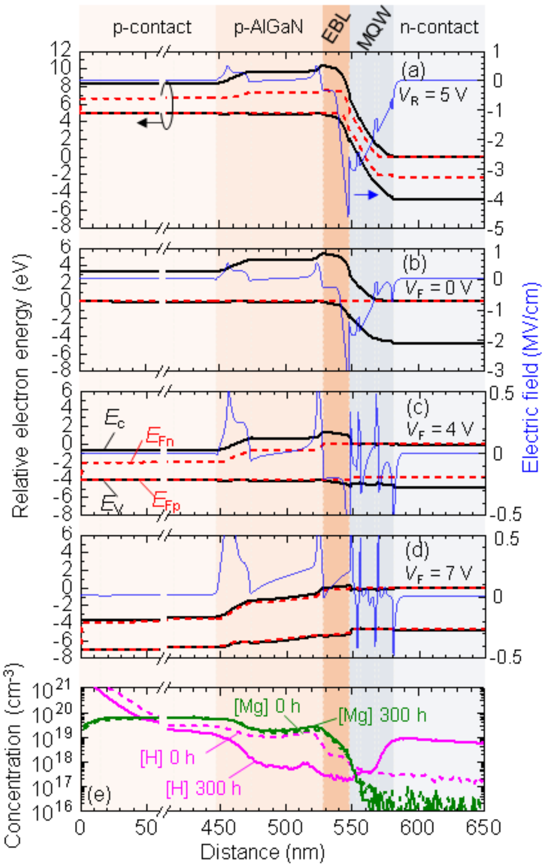

Fig. S3: Energy band profiles (black lines) and gross electric field (F) distributions (blue lines) of the LEDs calculated for (a) V_R = 5 V, (b) V_F = V_R = 0 V, (c) V_F = 4 V, and (d) V_F = 7 V, where E_{Fn} and E_{Fp} represent quasi Fermi levels for the electron and hole, respectively. In panels (a) - (d), relative electron energies are shown on left vertical axes and the electric fields ($F = -dE/dx$) are shown on right vertical axes, where positive F value indicates that F points from the surface (p) side to the bulk (n) side. (e) Concentration profiles of Mg ([Mg]) (green) and H ([H]) (magenta) quantified by SIMS measurement before (dotted lines) and after (solid lines) the operation for t_{op} = 300 h.