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A Mechanism for Mg Acceptor Activation in GaN by Low Energy Electron Beam Irradiation

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P-type conductivity is achieved in GaN by incorporating Mg acceptors using a two-step process. First hydrogen is introduced during growth to form $(Mg_{Ga}\text{-}H)^O$ complexes to inhibit Mg acceptor self-compensation by native donors defects , such as nitrogen vacancies, V_N. Second after growth Mg acceptors are activated by dissociating the $(Mg_{Ga}\text{-}H)^O \rightarrow Mg_{Ga}^- + H^+$ using rapid thermal annealing at ~700°C. Low energy electron beam irradiation (LEEBI) has also been used to activate acceptors in GaN:Mg using a conventional SEM, however, the exact mechanism for this effect is not completely understood.

LEEBI activation kinetics of GaN:Mg have been studied as a function of temperature (-190°C to 500°C), accelerating voltage (E_O), beam current (I_B) and irradiation time. The Mg acceptor concentration was monitored using scanning cathodoluminescence (CL) microscopy and spectroscopy. The experiments were conducted on 2µm thick GaN:Mg layers on sapphire with a [Mg] = 1×10^{19} cm^{-3} and a hole concentration of 1×10^{17} cm^{-3} as determined by Hall measurements. CL data were collected with a Gatan MonoCL3 system attached to a FEI Quanta 200 SEM.

Figure 1 and 2 show CL spectra before and after LEEBI irradiation at 25°C and -190°C respectively. LEEBI treatment at 25°C increases the intensity of a CL emission peak at 3.27 eV attributed to a free-to-bound (e,Mg°) transition, consistent with the creation of isolated Mg° acceptors following dissociation of $(Mg_{Ga}\text{-}H)^O$ complexes [1]. At -190°C the 3.28 eV ascribed to a donor-acceptor pair (DAP) transition involving a C_N acceptor is quenched by the LEEBI process leaving a broad peak due to a Mg related DAP centred at ~ 3.15 eV [2]. The rate of change of these CL bands was found to follow first order kinetics, scale directly with the electron beam injection fluence (Fig. 3) and decrease with increasing temperature up to ~260°C (Fig. 4).

First order kinetics are characteristic of bulk charge trapping. The density of trapped charge, $Q(t)$ cm^{-3}, can be expressed as $Q(t) = N_t[1-\exp(-t/\tau)]$, where $\tau = (\nu_{th}\sigma n_e)^{-1}$, ν_{th} is the thermal velocity of electrons, σ is the charge capture cross-section, N_t is the density of charge traps and n_e is the density of electrons. White the charge trapping rate can be written as $dQ(t)/dt \propto I_B R_e N_t \sigma$, where R_e is the electron range [3]. Due to the competitive nature of the CL recombination process, as charge traps fill these pathways close, increasing recombination through the $(Mg_{Ga}\text{-}H)^O$ channel. These centres dissociate because the recombination energy (~3.4 eV) is greater than the Mg-H binding energy (~ 1.6eV). Quenching of the 3.28 eV DAP band at -190°C occurs because the liberated H from the $(\mathrm{Mg_{Ga}}\text{-H})^{O}$ defects binds to the C_N acceptors forming stable (C_N-H) complexes [3]. The decrease in the LEEBI activation rate from -190°C to ~260°C is consistent with the proposed model as the charge traps depopulate $\propto \exp(-E_t/k_bT)$ with increasing T, where E_t is the trap depth energy. Above ~260°C thermal dissociation of the $(\mathrm{Mg_{Ga}}\text{-H})^{O}$ dominates the activation process. The results indicate that the LEEBI Mg acceptor activation rate in GaN is mediated by bulk charge trapping kinetics.

References

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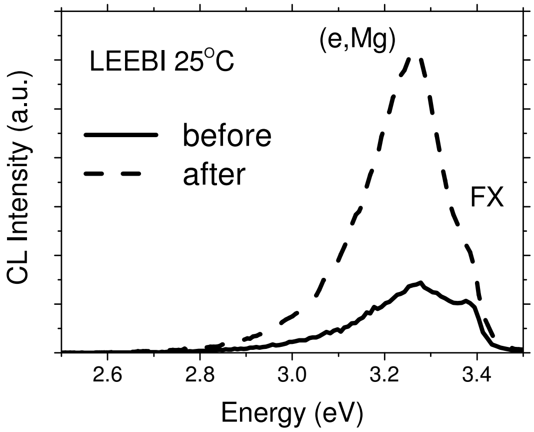

Figure 1 LEEBI at 25°C 60s 15 kV 7.1 nA 15 x 13 μm Spectra 15kV 7.1 nA 75 x 65 μm

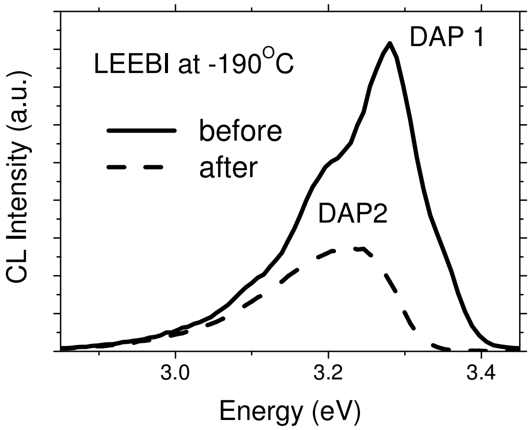

Figure 2 LEEBI at -190°C 60s 15 kV 7.1 nA 15 x 13 μm Spectra 15 kV 7.1 nA 75 x 65 μm

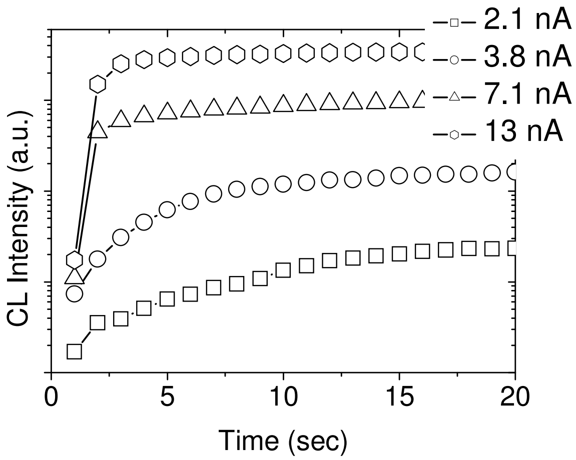

Figure 3 LEEBI I_B dependence at 25°C 15 kV 7.1 nA 15 x 13 μm

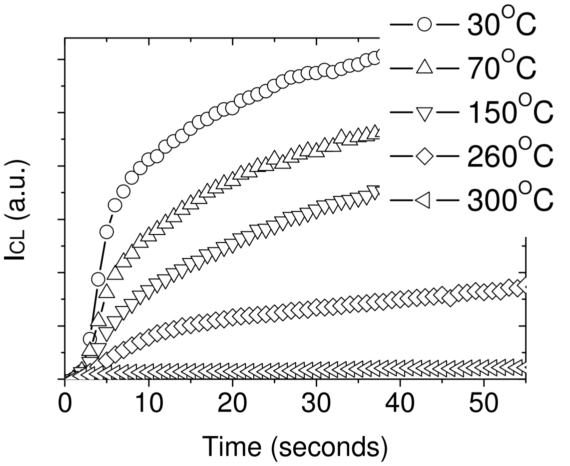

Figure 4 LEEBI temperature dependence 25°C 15 kV 7.1 nA 15 x 13 μm