## Yellow Luminescence in Gallium Nitride Induced by Intentional Impurity Incorporation During Halide Vapor Phase Epitaxy

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The 'yellow luminescence' (YL) band, often appearing in metalorganic vapor phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) grown GaN materials, is a broad defectrelated emission band around 2.2eV in the luminescence spectrum. The YL intensity depends on the specific growth technique and growth conditions employed. The physical or chemical origin of YL has not been unambiguously determined, nor has its electronic structure been clearly determined. In contrast to MOVPE and MBE-grown GaN, halide vapor phase epitaxy (HVPE) grown GaN films have no or very little YL. HVPE is therefore an ideal technique to investigate the origin of the YL through the intentional introduction of selected chemical impurities and/or under use of different growth conditions. The high growth rate of HVPE also makes it very useful in such studies since highly defected regions near the initial growth interface can be avoided in measurements on thick GaN films. We have employed HVPEgrown GaN to study the influence of carbon/hydrogen and hydrogen addition to the growth ambient on the appearance of the YL. Systematic enhancement of the YL has been found for both carbon and hydrogen in the growth ambient. The peak position, shape, intensity and temperature dependence of YL under these different experimental conditions are markedly different, indicating that there is more than one mechanism leading to the YL.

It was found that both the carbon and hydrogen-addition group samples emitted strong YL together along with the sharp bandedge luminescence. It is obvious that the YL bands in two cases are markedly different. They have different spectral shapes and peak positions. The YL band of the 'H<sub>2</sub>-growth' GaN contains a larger high-energy component than that of the C-doped GaN. The YL band of the C-doped GaN blue-shifted with the increasing temperature, while that of 'H<sub>2</sub>-growth' GaN red-shifted. The integrated intensity of the YL band of both C-doped and 'H<sub>2</sub>-growth' GaN samples could not be fit by a single exponential decay function. The activation energy at low temperatures of two samples could be calculated as 8.6 and 18 meV, respectively, implying that in both cases the radiative transition characterizing the YL most probably involves a shallow donor level and not a 'shallow' acceptor level.

All these HVPE-grown GaN samples have been processed using hydrogenation in flowing  $NH_3$  at 1000°C and dehydrogenation in flowing  $N_2$  at 800°C. The hydrogen induced yellow luminescence (YL) (~2.2-2.3eV) can be passivated by a high-temperature hydrogenation. This deactivation of the yellow luminescence is partially reversible. The low-energy component of this luminescence band can be effectively reactivated by a high-temperature  $N_2$  annealing, while the high-energy component of the YL band can not be recovered under the same condition. The reactivated part of the YL band can be passivated again by another hydrogenation process. Only the low-energy part of the YL band induced by the C-doping can be quenched by the hydrogenation and then be regenerated by the  $N_2$  annealing. In both cases, the high-temperature  $N_2$  annealing changes the PL properties only a little. The hydrogen passivation effects on both carbon and hydrogen induced YL have been explained by the formation of the neutral donor-hydrogen acceptor (D<sup>+</sup>-H<sup>-</sup>) complex in the GaN films.



Fig. 1 Low-temperature (20K) PL spectra of three typical HVPE-grown samples. There is no detectable YL signal in the spectrum of unintentionally doped GaN(A), while both spectra of C-doped(B) and "H<sub>2</sub>-grown"(C) exhibit strong YL bands. The dominant feature in the range of 3.0-3.47eV of the spectrum C is the signature of "H<sub>2</sub>-grown" GaN samples.



Fig. 2 PL spectra of the sample C in Fig. 1 under the conditions: as-grown (a), after hydrogenation (b), after hydrogenation and dehydrogenation (c), after the thermal cycle of hydrogenation-dehydrogenationhydrogenation (d), and after N<sub>2</sub>-ambient thermal annealing alone (e). All hydrogenation processing are performed under 1 atm in a flowing NH<sub>3</sub> at 1000°C for 0.5 hr. All dehydrogenation or N<sub>2</sub>ambient thermal annealing processing are completed under 1 atm in a flowing N<sub>2</sub> at 800°C for 0.5 hr. All PL spectra are taken at 20K using the 325 nm He-Cd laser line excitation with the pumping power density of 2.5 W/cm<sup>2</sup>. (b) and (d) clearly show that hydrogenating the GaN sample grown with H<sub>2</sub>-addition into the growth ambient can effectively passivate the YL band. (c) displays that the  $N_2$ ambient thermal annealing can reactivate the YL.