Molecular Beam Epitaxy of AlN and GaN Nanocrystals: Towards High Efficiency Deep Ultraviolet LEDs

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To date, it has remained difficult to achieve efficient LEDs operating in the ultraviolet (UV)-C band due to several critical challenges [1]: 1) poor p-type conduction of AlN and the resulting extremely low carrier (hole) injection efficiency, 2) very low quantum efficiency due to the presence of high densities of defects, and 3) poor light extraction efficiency associated with transverse-magnetic (TM) polarized emission for Al-rich AlGaN. Dislocation-free AlGaN nanocrystals have recently shown great promise to address these critical challenges. With the use of plasma-assisted molecular beam epitaxy (MBE), we have performed extensive studies of Mg-doped AlN nanocrystals. We show that, the use of N-rich conditions can significantly enhance Mg-dopant incorporation while suppressing N-vacancy related defect formation. The formation of Al-vacancy related defects, on the other hand, can be minimized by optimizing the growth temperature. Under optimized growth conditions, we demonstrate that large densities Mg-dopant ($\sim 1\times10^{20}$ cm^{-3}) can be incorporated in AlN. The resulting high concentrations of Mg-dopants lead to the formation of Mg impurity band and efficient hole hopping conduction. At room temperature, we measured free hole concentrations up to 6×10^{17} cm^{-3}[2], which is nearly seven orders of magnitude higher than that of Mg-doped AlN epilayer.

We have further investigated the epitaxy, fabrication, and characterization of large area AlN nanocrystal LEDs. The device exhibits strong electroluminescence emission at ~210 nm and excellent current-voltage characteristics, with a turn-on voltage ~6 V. The ideality factor is estimated to be ~4 and further increases with applied voltage, due to the tunneling of holes from the Mg impurity band to the valence band. We have also demonstrated deep UV LEDs by incorporating single and double monolayer GaN active regions, respectively. Such dislocation-free GaN monolayer structures can exhibit transverse-electric (TE) polarized emission in the deep UV spectrum and have reduced quantum-confined Stark effect due to the extreme quantum confinement. The controlled formation of single and double monolayer GaN was further confirmed by HAADF-STEM analysis. AlN nanowire LEDs with GaN monolayers incorporated were further fabricated. For the monolayer GaN sample, the emission peak is at 238 nm. The light intensity increases near-linearly with increasing current. The peak emission wavelength stays nearly invariant with increasing current, due to the extreme quantum-confinement. Work is currently in progress to achieve deep UV LEDs with high power operation by enhancing the light extraction efficiency utilizing AlGaN photonic nanocrystals and by optimizing the device fabrication process.

[1] H. Hirayama, N. Maeda, S. Fujikawa, S. Toyoda and N. Kamata, Jpn. J. Appl. Phys. **53**, 100209(2014).
[2] N. Tran, B. Le, S. Zhao and Z. Mi, Appl. Phys. Lett. **110**, 032102(2017).

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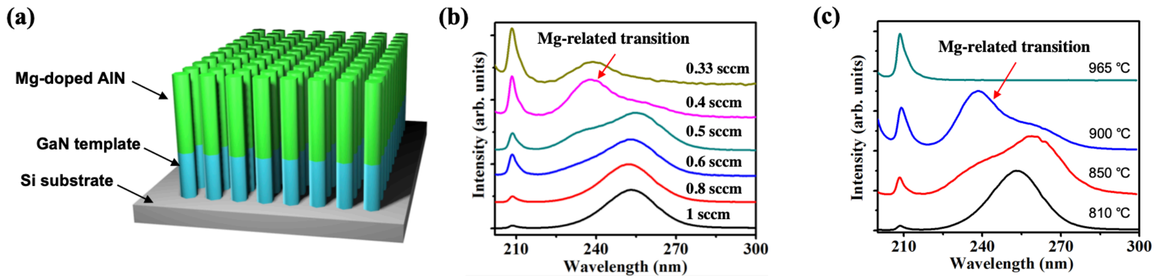

Figure 1. (a) schematic of Mg-doped AlN nanocrystals grown on Si substrate. Room temperature photoluminescence of Mg-doped AlN nanocrystals grown under (b) varying nitrogen flow rate and (c) varying substrate temperature. The pronounced Mg-acceptor related transition can be clearly measured (indicated by the red arrow).

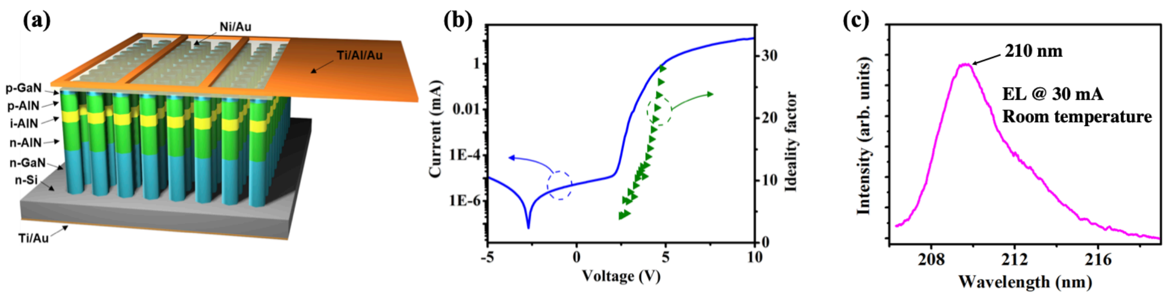

Figure 2. (a) schematic illustration of the fabricated large area AlN deep UV LED. (b) Current-voltage (I-V) characteristics measured at room temperature. (c) Room-temperature electroluminescence (EL) spectrum measured from AlN LEDs.

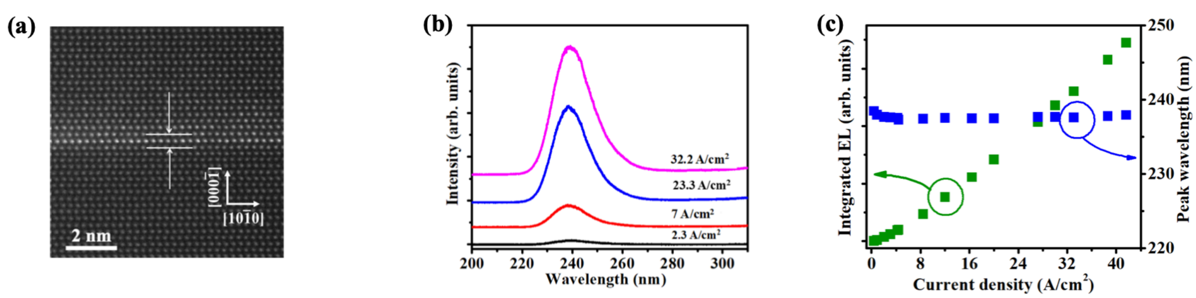

Figure 3. (a) STEM-HAADF images of one monolayer GaN quantum disk embedded in AlN matrix. (b) Electroluminescence spectra measured under injection currents from 2.3 A/cm^2 to 32.2 A/cm^2 for the monolayer GaN LED. (c) Variations of the integrated electroluminescence intensity (green) and peak position (blue) vs. injection current. The measured device size is 300 μm × 300 μm.