Deep-UV LEDs using polarization-induced doping: Electroluminescence at cryogenic temperatures

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Traditional impurity doping schemes are difficult for extreme-gap semiconductors, such as high Al content AlGaN alloys due to the large activation energies for donors and acceptors. Polarization-induced (or Pi-) doping, since its first demonstration [1], is being gradually implemented as an attractive alternative for effective p-type doping in large-bandgap nitride semiconductors both for power electronics, and for deep-UV photonics. Because mobile carriers are field-ionized instead of thermal ionization, they do not freeze out even at cryogenic temperatures. In this work we demonstrate polarization-induced doping deep-UV LEDs emitting in the 235-260 nm (5.25 to 4.75 eV) spectral range at both room temperature and at cryogenic temperatures. The effectiveness of polarization-induced doping is highlighted by a ~300% increase in the deep-UV EL intensity at 4K compared to the value at 300K.

In prior studies, we reported deep UV LEDs [2] with Pi-doping of p-AlGaN contacts. In this work we realize for the first time, a planar deep UV LED in which both the n- and p-AlGaN regions are with Pi-doped, showing EL at ~260 nm. The heterostructure was grown by RF-plasma MBE on AlN-on sapphire templates. Three ~100 nm linearly graded AlGaN layers comprise the LED structure (Fig. 1): i) graded-down Si-doped buffer layer, ii) graded-up Pi+Si doped n-type layer, and iii) graded-down Pi-+Mg doped p-type layer.

For the optically active region for generation of deep-UV photons, 4X ultra-thin GaN quantum dot (QD) /AlN barrier heterostructure was inserted between the doped regions. 2 monolayer (ML) thick GaN QDs were grown in the Stranski-Krastanov mode between 2.5 nm thick AlN barriers. The thin barriers are suitable for tunnel injection of carriers into quantum dots leading to a) lower turn-on voltages and b) temperature independent LED operation. The STEM image in Fig. 1 and the complementary EDX spectra confirms the successful realization of the linearly graded heterostructures. The MBE heterostructures were then processed into standard mesa-LED structures.

The processed LEDs were then characterized for temperature-dependent electroluminescence (EL). A 261 nm peak emission was observed at room temperature with a low turn-on voltage between 5V and 6V. A monotonic increase in the EL intensity was observed with applied bias over 4V→8V range. Similar measurements at low temperature down to 4K showed a blue shift in the emission peak from 261 nm to 255 nm. A secondary peak at 237 nm is attributed to a bi-modal size distribution of the GaN QDs. The LED turn-on voltage remained less than 6V at 4K. Higher current densities at 4K for similar applied voltages suggest that the Pi-doped graded layers are more conductive at low T (Fig. 2(b)). The integrated EL between 300K and 4K (Fig. 2 (c)) showed more than 3X enhancement of deep-UV light emission at 4K. This is a signature of the effectiveness of Pi- doping. Since the Pi-doping is independent of temperature, holes and electrons can be injected into LED active area at cryogenic temperatures. The enhanced electroluminescence at 4K is due to both increased current injection and improved radiative efficiency. On the other hand, a conventional impurity doped LED at low temperatures leads to more resistive contacts and therefore should dramatically reduce electroluminescence intensity at the same bias. We experimentally confirmed this by measuring EL intensity of a deep UV LED with a polarization p-doped region, but a conventionally doped n-region. Fig. 2 (d) shows ~30X quenching of EL as the temperature reduces to 220K. This constitutes the first demonstration of the effectiveness of a Pi-doped planar deep UV LED.

References:

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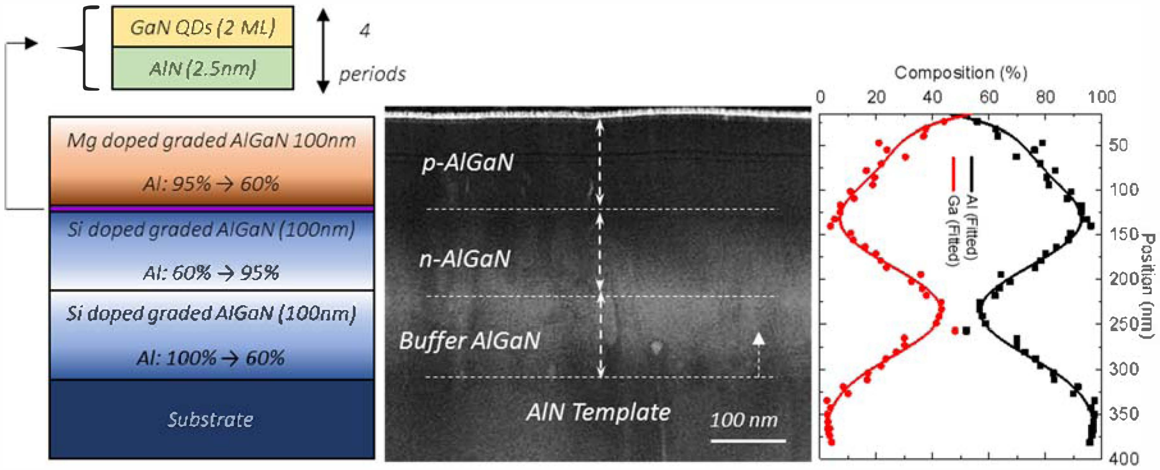

Fig 1: (Left) Schematic of the structure, (middle) Z-contrast STEM image showing graded layers, (right) linear grading confirmed from EDX spectral scan.

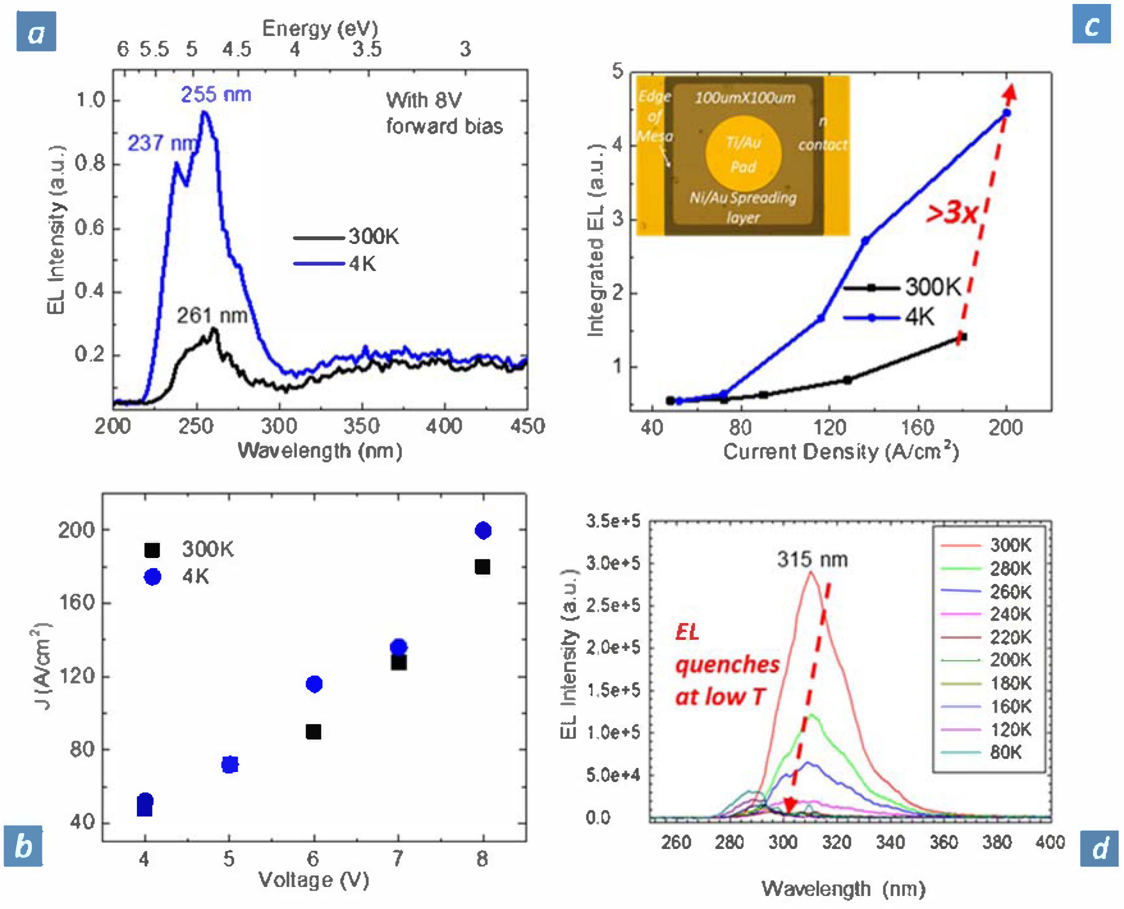

Fig 2: (a) Electroluminescence of processed LED with 8V forward bias at 300 K and at 4K. (b) J-V characteristics show decrease of device resistivity at low temperature. (c) Comparative integrated EL confirms more than 3 times enhanced emission at cryogenic temperature. Inset shows top view of a processed device. (d) EL quenches rapidly at low temperature for LED having pseudo-polarization doped layers.

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