Quantum and Nanoscale Engineering of Al(Ga,B)N for High Efficiency UV-C and Far UV-C Optoelectronics

Zetian Mi
Department of Electrical Engineering and Computer Science, University of Michigan
1301 Beal Ave., Ann Arbor, MI 48109, USA

AlGaN-based UV-C and far UV-C light emitting diodes (LEDs), in the wavelength range of ~200-280 nm, are highly desired for water and air purification and disinfection. To date, however, due to the large lattice mismatch, poor p-type conduction, and inefficient light extraction, it has remained extremely challenging to achieve high efficiency UV-C and far UV-C LEDs. These critical issues, together with the large transparency carrier density of ultrawide bandgap semiconductors, have also made it very difficult to realize low threshold deep UV laser diodes [1]. Recent studies suggest that some of these critical challenges can be addressed through nanoscale and quantum engineering of III-nitride semiconductors. Due to the efficient strain relaxation, dislocation-free Al(Ga,B)N nanostructures can be epitaxially grown directly on foreign substrates. Recent advances in selective area epitaxy have further shown that their properties can be precisely controlled, resulting in superior quality nanocrystals that are device worthy. Also due to efficient strain relaxation, Al (or Ga)-substitutional Mg formation energy is significantly reduced in nanocrystals, leading to relatively efficient p-type conduction of AlN [2]. Improved p-type conduction has also been achieved in Al-rich AlGaN using a new epitaxy process – *in situ* tuning of the surface Fermi level, which significantly enhances the incorporation of Mg-acceptors without the formation of extensive compensating defects [3]. These advances have enabled the realization of tunnel junction UV-C and far UV-C LEDs with improved performance, including high external quantum efficiency (EQE) and high electrical efficiency [4]. Recent studies further suggest that high luminescence emission efficiency in the deep UV can be realized by exploiting strong quantum confinement of charge carriers, through either the formation of quantum dot-like nanoclusters or monolayer hBN. Significantly, the three-dimensional quantum confinement of charge carriers can drastically reduce the transparency carrier density of ultrawide bandgap semiconductors, which, together with the relatively efficient p-type conduction, can lead to electrically pumped UV laser diodes with low threshold operation [5]. In this talk, I will present an overview of some recent advances of nanoscale and quantum engineering of III-nitride heterostructures that are relevant for the development of UV-C and far UV-C LEDs and laser diodes [6]. The epitaxy, structural, optical, electrical, and excitonic properties of Al(Ga)N nanostructures and monolayer hBN will be presented. Improved design of UV-C and far UV-C optoelectronics, including the incorporation of tunnel junction, electron blocking layers and photonic crystals, will be presented, followed by discussions on the performance characterization of Al(Ga)N and hBN based UV-C and far UV-C optoelectronics, including LEDs and laser diodes.

References:

[1] Z. Zhang, M. Kushimoto, T. Sakai, N. Sugiyama, L.J. Schowalter, C. Sasaoka and H. Amano, Appl. Phys. Express. 12, 124003, (2019).
[2] N.H. Tran, B.H. Le, S. Zhao, and Z. Mi, Appl. Phys. Lett. 110, 032102, (2017).
[3] A. Pandey, X. Liu, Z. Deng, et al., Phys. Rev. Mater. 3, 053401, (2019).
[4] A. Pandey, W.J. Shin, J. Gim, R. Hovden, and Z. Mi, Photon. Res. 8, 331, (2020).
[5] K.H. Li, X. Liu, Q. Wang, S. Zhao, and Z. Mi, Nature Nanotechnology 10, 140, (2015).
[6] X. Liu, A. Pandey, and Z. Mi, Jap. J. Appl. Phys. 60, 110501, (2021).