Study on the Quantum Efficiency Enhancement in AlInN Nanowire Light-Emitting Diodes Grown by Molecular Beam Epitaxy

Ravi Teja Velpula, Barsha Jain, and Hieu P. T. Nguyen*
Department of Electrical and Computer Engineering
New Jersey Institute of Technology
New Jersey, USA, 07102
*E-mail: hieu.p.nguyen@njit.edu

***Abstract* — We report on the demonstration of electron blocking layer free AlInN nanowire light-emitting diodes (LEDs) operating in the 280-365 nm wavelength region. The molecular beam epitaxial grown AlInN nanowires have a relatively high internal quantum efficiency of > 52%. Moreover, we show that the light extraction efficiency of the nanowires could reach ~ 63% for hexagonal photonic crystal nanowire structures which is significantly higher compared to that of the random nanowire arrays. This study provides significant insights into the design and fabrication of a new type of high-performance AlInN nanowire ultraviolet light-emitters.**

Keywords— nanowire; AlInN; light-emitting diodes

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I. Introduction

High-efficiency ultraviolet (UV) light-emitting diodes (LEDs) are in high demand due to their wide range of applications [1,2]. AlGaN semiconductor has been intensively studied for high-efficiency UV LEDs due to its wide bandgap optical tuning from 200-365 nm. However, AlGaN based UV LEDs exhibit low external quantum efficiency (EQE) and low output power. Identifying and developing the potential of alternative UV materials will be critical to make further progress in the development of UV emitters. In this regard, AlInN alloy has not been widely studied even though it holds great potential application in UV and visible light-emitting devices. In this context, we have designed and fabricated AlInN nanowire LEDs with strong emission in the UV wavelength regime. The AlInN nanowires have high internal quantum efficiency (IQE) of >52% and significantly strong TM polarized emission at 299nm.

II. Experiment, Results and Discussion

Vertically aligned AlInN nanowire LED structures were spontaneously grown on *n*-Si (111) substrates under nitrogen-rich conditions by a Veeco GEN II MBE system. The growth conditions for GaN nanowire segments include a growth temperature of ~ 800 °C, nitrogen flow rate of 0.5-1.0 sccm, and forward plasma power of ~ 400 W. The device active region consists of ~ 100 nm n-$Al_{0.78}In_{0.22}N$, 40 nm undoped $Al_{0.75}In_{0.25}N$ well and 100 nm p-$Al_{0.78}In_{0.22}N$ layers. The nanowire LED samples were fabricated using standard lithography method as reported elsewhere [3,4]. Figure 1(a) shows the 45° tilted scanning electron microscope image of a standard AlInN nanowire LED sample. The nanowires have relatively uniform morphology and size with a wire diameter of 80 - 100 nm. Figure 1(b) presents the schematic illustration of a single nanowire LED structure.

Photoluminescence (PL) spectra of AlInN nanowire were measured using a 266 nm diode-pumped solid-state laser as the excitation source at room-temperature. The peak emissions of the AlInN nanowires vary from 280nm to 365nm by controlling the Al/In composition in the AlInN layers. The AlInN/GaN nanowire exhibits relatively high IQE which is estimated of ~ 52% at room temperature. Illustrated in Fig. 2, strong emission spectra at ~299 nm without an obvious shift in the peak wavelength were recorded, confirming the high AlInN nanowire crystalline quality and reduced quantum-confined Stark effect.

The light extraction efficiency (LEE) of the AlInN nanowire UV LEDs was studied by using finite difference time domain (FDTD). Spontaneously grown nanowires and nanowires arranged in hexagonal photonic crystal array are used in this investigation. The average LEE for the spontaneously grown nanowires was observed to be around only 20% to 35%. However, the LEE is estimated for the hexagonal photonic crystal arrangement for nanowire radius of 60 nm and spacing ranges from 145 nm to 300 nm. The maximum LEE value for the photonic crystal array is found to be ~63% for the spacing of 235 nm, illustrated in Fig. 3(a). Moreover, the results for the AlInN nanowires support the dominant vertical emission (top) of the LEE, although the nanowire structures highly favor TM-polarized emission, as shown in Fig. 3(b).

III. Conclusion

In summary, AlInN UV nanowire LEDs with stable and strong emission have been demonstrated. Moreover, the LEE of the AlInN nanowire LEDs could be enhanced by almost two times using hexagonal photonic crystal arrangement. This study provides a promising approach for the development of high-efficiency UV nanowire LEDs using AlInN semiconductor.

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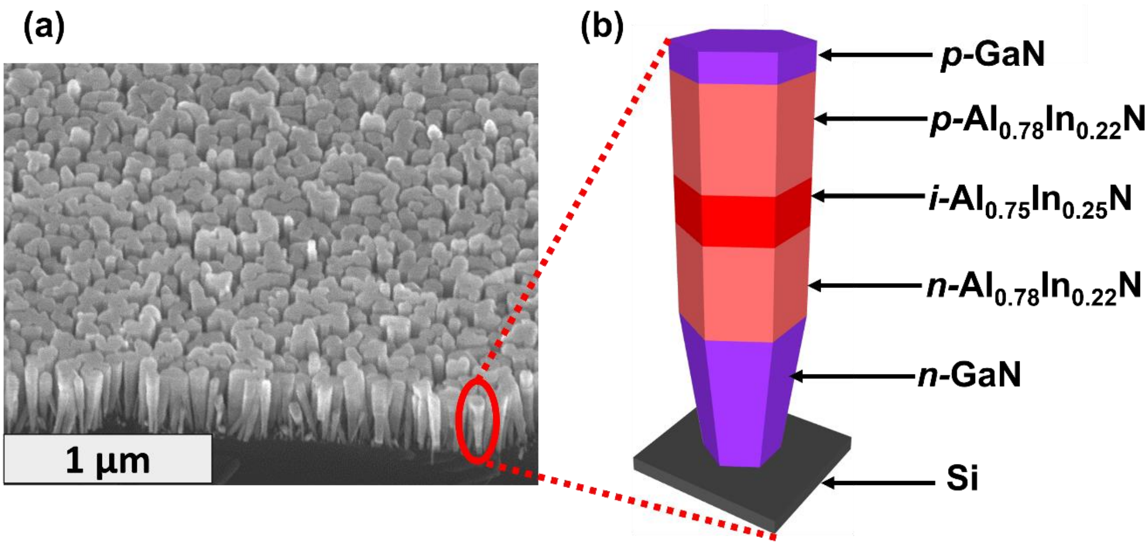

Fig. 1. (a) 45° tilted scanning electron microscope image of AlInN nanowires on Si (111) substrate. (b) Schematic structure of an AlInN nanowire UV LED.

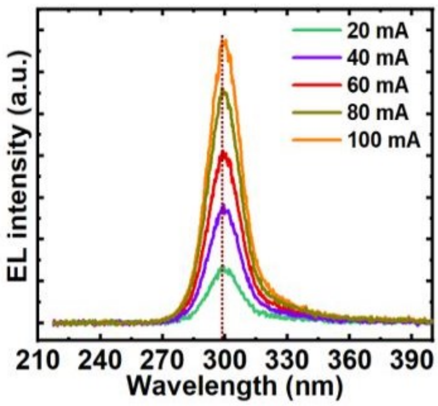

Fig. 2. Electroluminescence spectra of AlInN nanowire UV LED.

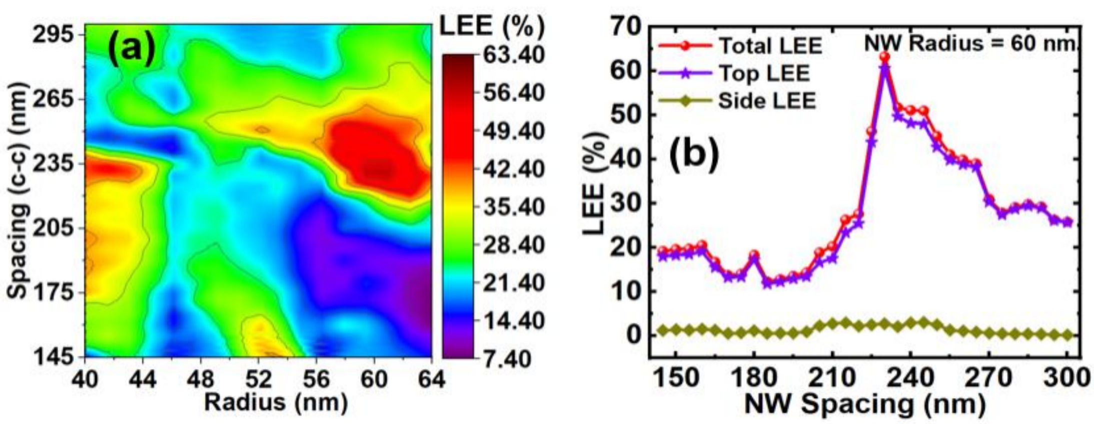

Fig. 3. (a) Contour plot of the LEE vs. nanowire radius and spacing for hexagonal array of AlInN nanowire UV LEDs. (b) LEE vs nanowire spacing for hexagonal array of UV nanowire LEDs for nanowire radius = 60 nm.