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(Invited) Enhanced Efficiency of AlInN Nanowire Ultraviolet Light-Emitting Diodes Using Surface Passivation and Photonic Crystal Structures

Ravi Teja Velpula, Moulik Patel, Barsha Jain, Andressa Marangon, and Hieu Pham Trung Nguyen*

Electrical and Computer Engineering Department, New Jersey Institute of Technology, Newark, NJ 07102, USA
*Email: hieu.p.nguyen@njit.edu

In this paper, we report on the enhanced light extraction efficiency (LEE) of AlInN nanowire ultraviolet light-emitting diodes (LEDs) at an emission wavelength of 283 nm using the surface passivation approach and hexagonal photonic crystal structures. Several dielectric materials including SiO_2, Si_3N_4, HfO_2, AlN, and BN, have been investigated as the surface passivation layer for the AlInN nanowire LEDs. The LEDs using these dielectric materials show significantly improved LEE compared to that of the unpassivated ultraviolet nanowire LEDs. With a 35nm Si_3N_4 as surface passivation, the AlInN LED could achieve a LEE of ~ 42.6%, while the unpassivated LED could only have an average LEE of ~ 25.2%. Moreover, the LEE of the AlInN nanowire LEDs could be further increased using hexagonal photonic crystal structures. The periodically arranged nanowire LED arrays could reach up to 63.4% which is almost two times higher compared to that of the random nanowire LEDs. Additionally, the AlInN nanowire ultraviolet LEDs exhibit highly transverse-magnetic polarized emission.

Introduction

High-efficiency ultraviolet (UV) light-emitting diodes (LEDs) are in high demand for a wide range of applications [1-4]. Due to its wide bandgap, covering from deep UV to near visible, AlGaN semiconductor has been intensively studied for high-efficiency UV LEDs. However, the performance of AlGaN UV LEDs is still limited, especially in the deep UV wavelength region, due to large dislocation density, extremely inefficient *p*-type doping in AlGaN film, and some other limiting factors [5-7]. Therefore, AlGaN UV LEDs have been suffering from low internal quantum efficiency (IQE), poor light extraction efficiency (LEE), and low external quantum efficiency (EQE). Alternatively, AlInN alloy is relatively unexplored for light-emitters even though it holds great potential application in UV and visible light-emitting devices. We have recently demonstrated the first AlInN nanowire UV LEDs with emission wavelength could be tuned from 290 nm - 365 nm [8]. The AlInN nanowire LEDs exhibit a high IQE of ~ 52% and dominant transverse-magnetic (TM) polarized emission [8]. Moreover, the AlInN nanowire LEDs could obtain higher IQE and output power compared to the AlGaN UV LEDs due to the enhanced carrier transport and reduced electron overflow [9]. However, the performance of the AlInN nanowire LEDs still suffers from the strong surface nonradiative recombination and poor LEE [10-14]. In this context, by using the finite-difference time-domain (FDTD) simulations, we have systematically studied the LEE of AlInN nanowire UV LEDs using dielectric-based surface passivation and photonic crystal to reduce the surface nonradiative recombination and to increase the LEE. Different dielectric materials that include SiO_2, Si_3N_4, HfO_2, AlN, and BN have been investigated as surface passivation layers for the AlInN nanowires. While the unpassivated LEDs have LEE of ~25.2%, the LEDs employing these passivation layers show significantly enhanced LEE. For instance, AlInN LED with 35nm Si_3N_4 could obtain high LEE of ~ 43.5%. However, it is challenging to achieve uniform passivation layer around the nanowire arrays since the spacing between nanowires is narrow and is not well controlled in randomly arranged nanowire arrays. Nonetheless, a selective area growth technique has been successfully introduced to fabricate nanowire arrays with well-controlled nanowire radius, spacing, and morphology. In this study, we have shown that the AlInN nanowire UV LEDs could reach unprecedentedly high LEE of > 63% by using hexagonal photonic crystal nanowire structures which is more than 2 times higher than that of the random nanowire LEDs. [15-17].

Molecular Beam Epitaxial Growth, Device Fabrication, and Characteristics of AlInN Nanowire UV LEDs

The AlInN nanowire LED structures were spontaneously grown on *n*-Si (111) substrates under nitrogen-rich conditions by a Veeco GEN II molecular beam epitaxy (MBE) system. The device active region consists of ~ 100 nm *n*-$Al_{0.82}In_{0.18}N$, 40 nm undoped $Al_{0.78}In_{0.22}N$ well and 100 nm *p*-$Al_{0.82}In_{0.18}N$ layers. The GaN nanowire segments were grown at ~ 800 °C, nitrogen flow rate of 0.5-1.0 sccm, and forward plasma power of ~ 400 W. However, the growth temperature of the active region was at ~ 670 700 °C to increase the In incorporation in AlInN segments and the nitrogen flow rate was kept at 2.5 sccm. The MBE grown AlInN under nitrogen-rich condition offers an effective approach to eliminate the composition inhomogeneity in the AlInN. The nanowires are vertically aligned to the Si substrate with a quite uniform dimension, as illustrated in Figure 1(a). Figure 1(b) presents the schematic structure of a single AlInN nanowire LED.

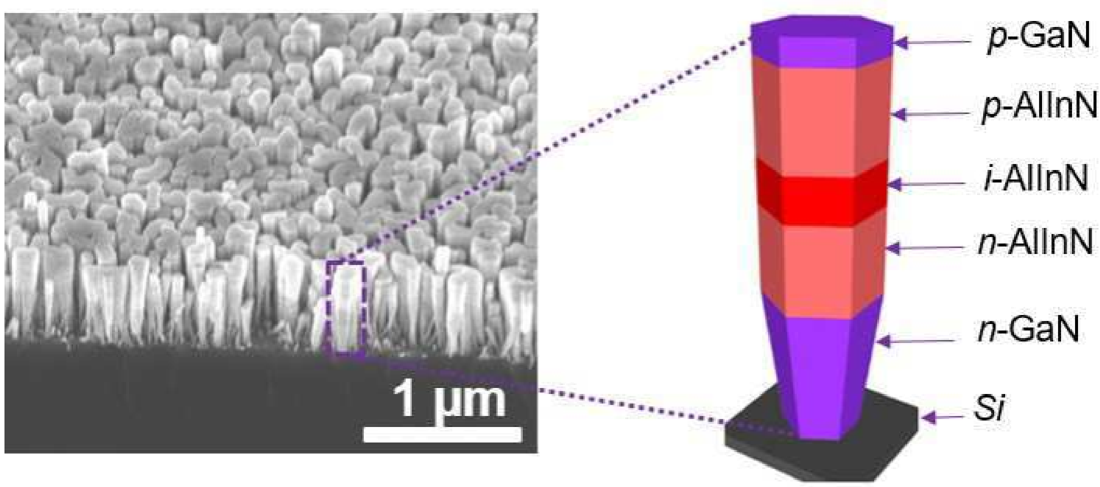

Figure 1. (a) 45° tilted SEM image of AlInN nanowire UV LEDs on Si. (b) Schematic structure of the AlInN nanowire UV LED.

The photoluminescence (PL) spectra of AlInN nanowires were measured using a 266 nm diode-pumped solid-state laser as the excitation source. Figure 2(a) presents the PL spectra of the AlInN nanowire UV LED with a strong peak emission at ~ 283nm originating from the emission of the AlInN active region. The emission from the GaN layers is presented as the peak emission at ~ 360nm. The luminescence from AlInN quantum barriers is not presented since their peak emissions are shorter than 266nm. Moreover, the peak emissions of the AlInN nanowires can be varied from 280nm to 365nm by varying the Al/In composition in the AlInN layers. The peak emission is shifted to a shorter wavelength when the substrate temperature gets increase which is attributed to the increased In adatom desorption at higher growth temperature, resulted in the reduced In composition in the AlInN segment. The AlInN/GaN nanowire exhibits relatively high IQE which is estimated of ~ 52% at room temperature.

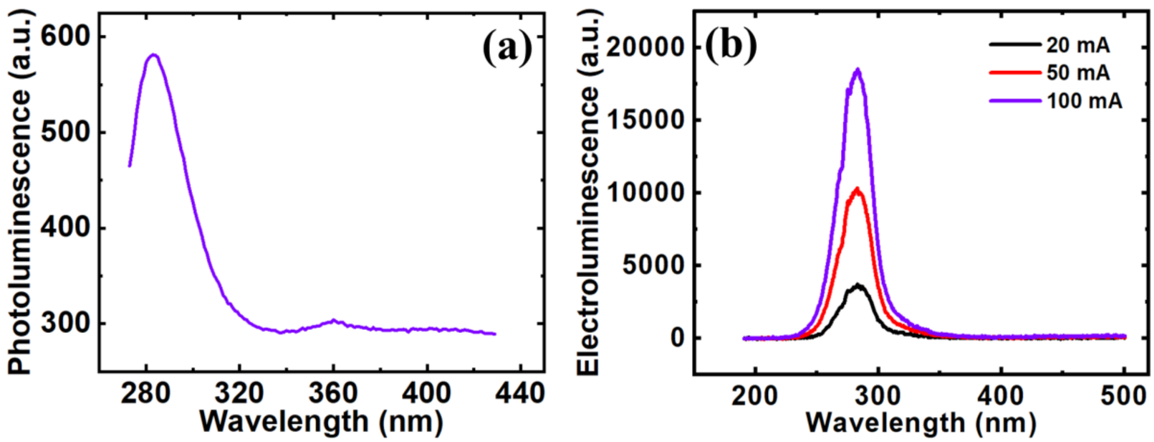

Figure 2. Room temperature (a) Photoluminescence (b) electroluminescence under different injection currents of the AlInN nanowire UV LEDs.

The AlInN nanowire LED fabrication process includes standard procedures that include surface planarization, oxygen plasma dry etching, photolithography, metal deposition and annealing. The detailed fabrication method is presented in our previous publications [18]. The 500×500 μm^2 UV LEDs are chosen for further characterization. As illustrated in Figure 2(b), the UV nanowire LED holds strong emission at ~283 nm with a negligible shift in the peak wavelength, attributing to the high crystalline quality and reduced quantum-confined Stark effect in the AlInN nanowires. The LED has a low turn-on voltage of ~5V and a low reverse leakage current, i.e., ~ 0.5 μA at -8.6V.

Study on the LEE enhancement in AlInN nanowire UV LEDs

In this study, we have carefully calculated the LEE of the AlInN nanowire UV LEDs using three-dimensional FDTD computational method [19]. The simulated LED contains 200 nm *n*-GaN, 100 nm *n*- $Al_{0.82}In_{0.18}N$ QB, 40 nm *i*- $Al_{0.78}In_{0.22}N$ QW, 100 nm *p*-$Al_{0.82}In_{0.18}N$ QB, and 20 nm *p*-GaN layer. Here the LEE has been estimated by placing a single TE or TM polarized dipole source with a 283 nm emission wavelength in the middle of the QW. TE polarization defines the major electric field that travels in the in-plane direction [E ⊥ c-axis]. TM polarization is represented by the major electric field traveling in the out-of-plane direction [E // c-axis]. We have encapsulated the entire nanowire structure with 12 perfectly matched layer (PML) boundary conditions in order to avoid the reflections of outgoing waves back into the simulation space [20]. Moreover, source power monitors are placed around the single dipole source to measure the total power generated in the active region accurately. Finally, we have calculated the LEE of nanowire LED which is the ratio of the light output power measured by the output power monitors to the total emitted power in active region measured by the source power monitor [21].

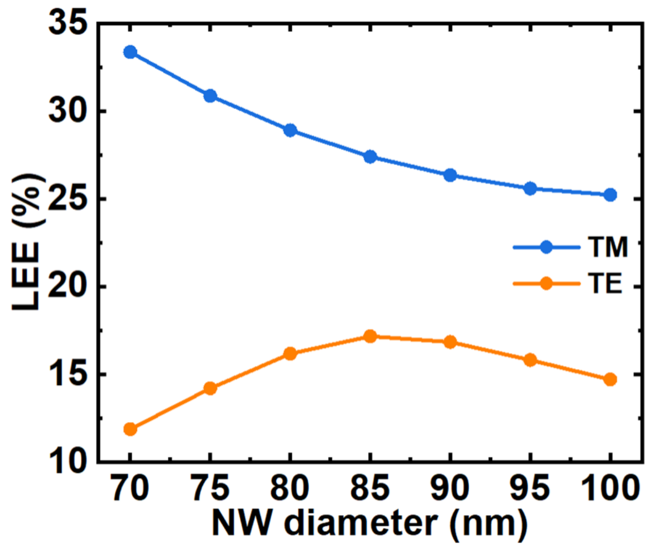

Figure 3. LEE of the AlInN nanowire UV LEDs as a function of nanowire diameter.

First, the LEE of AlInN nanowire UV LED is investigated for both TE- and TM-polarizations as a function of nanowire diameter. Figure 3 shows the LEE as a function of nanowire diameter ranging from 70 nm to 100 nm at 65 nm tapered *n*-GaN diameter. The result shows that AlInN nanowire LED favors TM-polarized emission than TE-polarized emission due to reported higher TM-polarized LEE. For instance, the maximum LEE is ~33.35% at 70 nm nanowire diameter can be achieved for TM-polarized emission while LEE obtained due to TE-polarized emission is only ~17.16% at 85 nm diameter. However, with the increase in the nanowire diameter, LEE for TM polarized light is reducing. The trapping of photons becomes more obvious for TM- polarizations due to the weak micro-cavity effect with the increase in nanowire diameter. The strong photons confinement inside the nanowire structure for both polarizations results in a lower LEE [22].

One of the prominent reasons behind holding the performance of nanowire LEDs is surface states such as dangling bonds and Fermi-level pinning on the nanowire surface that greatly contribute to high surface nonradiative recombination thereby reducing the performance of the nanowire UV LEDs [23]. In this context, the passivation of nanowire LED plays a vital role in mitigating the surface nonradiative recombination arising from the surface states. However, the passivation layer can also probably impede the light extraction if the design is not well optimized in terms of passivation layer materials and its thickness. The calculated LEE values of AlInN nanowire LED with 100 nm nanowire diameter for TM polarized light sources with various thicknesses of SiO_2, Si_3N_4, HfO_2, AlN, and BN passivation layers ranging from 5 nm to 60nm are shown in Figure 4. It is seen that passivation layer thickness has a clear impact on the LEE in addition to its critical parameters such as the refractive index and the absorption coefficient. Illustrated in Figure 4, all passivation layers follow a similar trend in that the LEE is increased with the passivation layer thickness and recording its maximum LEE. After that particular passivation layer thickness, it is seen that the LEE is decreased as the thickness of the passivation layer is increased. This is due to the enhanced total internal reflection and coupling of resonant modes between the nanowire core and the passivation layer. Here, Si_3N_4 recorded the highest LEE of 42.6% at 35 nm passivation layer thickness, while BN reported the lowest LEE of 16.5% at 60 nm passivation layer thickness. It is worth mentioning, that with SiO_2 material, observed the maximum and minimum LEEs like with all other passivation materials but in the range of 5-100 nm thickness.

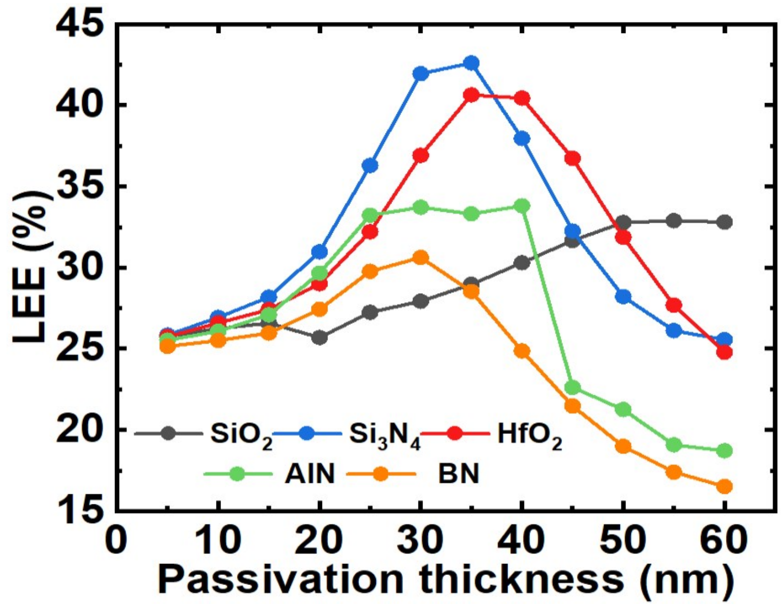

Figure 4. LEE of the AlInN nanowire UV LEDs with different passivation materials as a function of passivation layer thickness.

Finally, we have estimated the LEE of LEDs with randomly grown nanowires and hexagonal nanowire arrays with the same number of nanowires in each case. The average LEE was observed to be around 20% to 25% for random LED. The LEE of hexagonal nanowire array LED as a function of the spacing between nanowires and diameter of nanowires is shown in Figure 5. The maximum LEE is found to be ~ 63.4% for the spacing of 230 nm and diameter of 120 nm. It can be understood that the nanowires arrangement and geometry play an important role in directing the generated photons from the active region to the air [18].

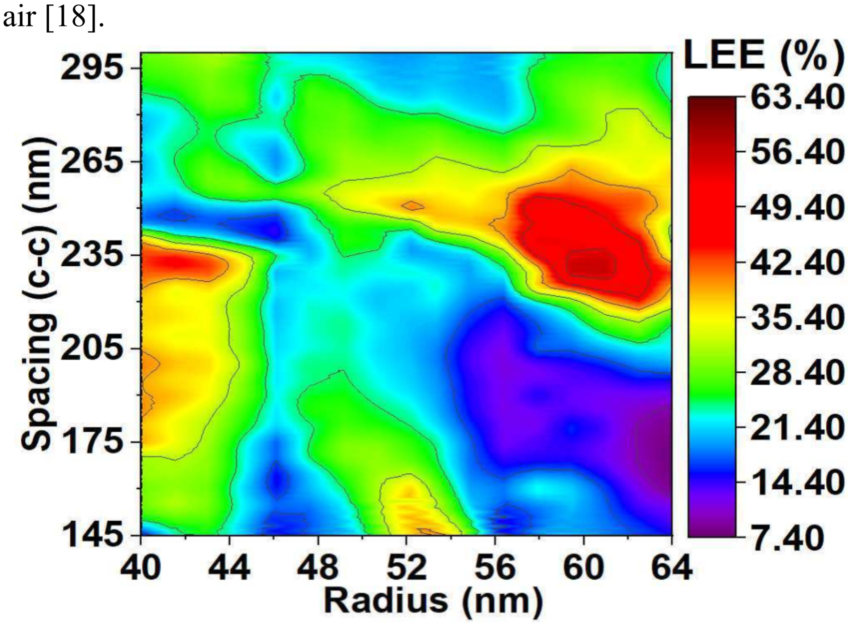

Figure 5. Calculated LEE vs. radius and spacing between nanowires of hexagonal array AlInN nanowire UV LEDs.

Conclusion

In conclusion, AlInN UV nanowire LEDs with stable and strong emission have been demonstrated at 283 nm wavelength. We have analyzed the impact of the nanowire diameter on LEE. Further, the LEEs of these LEDs have been enhanced employing optimized passivation layer. Importantly, the LEE of the AlInN nanowire LEDs could be increased by more than two times using hexagonal photonic crystal nanowire arrays. This work paves the way for the design and fabrication of high-power deep UV LEDs those can be utilized in practical applications.

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