Improving the Efficiency of Transverse Magnetic Polarized Emission from AlGaN Based LEDs by Using Nanowire Photonic Crystal

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Abstract: AlGaN-based deep ultraviolet (UV) light-emitting diodes (LEDs) are attractive for a wide range of applications. To date, however, the best reported external quantum efficiency (EQE) for LEDs operating in the wavelength range of ∼240 nm is well below 1%. In this paper, we have performed detailed studies of the EQE of AlGaN nanowire photonic crystal LEDs in this wavelength range by finite-difference time-domain simulation. By coupling in-plane emission to vertical emission, light-extraction efficiency (LEE) over 90% can, in principle, be expected from the device top surface for transverse magnetic polarized photons that was not previously possible in conventional planar quantum well devices. Taken into account practical limitations including the absorptive p-Al(Ga)N contact and the presence of metal contact grid, LEE in the range of 30–40% is also expected. Moreover, due to the Purcell effect, the radiative recombination rate and, therefore, internal quantum efficiency (IQE) can be significantly modified in nanowire photonic crystal structures. We have established the design principles and ultimate efficiency limit of AlGaN nanowire photonic crystal LEDs: For AlGaN LEDs with very high IQE, EQE > 70% can, in principle, be expected by operating near the Γ point of nanowire photonic crystals, whereas for structures with relatively low IQE it is preferred to operate near the M point to enhance the IQE while maintaining reasonably high LEE.

Index Terms: Light extraction, Purcell effect, photonic crystal, AlGaN nanowire, deep UV LED.

1. Introduction

Semiconductor light emitters, including light emitting diodes (LEDs) and lasers that can operate efficiently in the deep ultraviolet (UV) wavelength range are essentially required for a broad range of applications, including water purification, disinfection, and chemical and biochemical sensing [1]–[7]. AlGaN alloys have direct energy bandgap in the wavelength range of ∼200 nm to 360 nm and have emerged as the material of choice for UV optoelectronics. To date, however, it has remained extremely challenging to achieve high efficiency AlGaN deep UV light emitters particularly...
for high AlN content with emission wavelengths between ~200 nm and 240 nm. For example, the best reported external quantum efficiency (EQE) for LEDs operating in the wavelength range of 240 nm is well below 1% [8]–[10]. Among the reasons for low EQE, there is a problem of the light extraction of the dominant transverse magnetic (TM) polarized emission \( \mathbf{E} \parallel c \)-axis) at high AlN content, in addition to the low injection efficiency and the low internal quantum efficiency (IQE) due to the presence of large densities of defects and dislocations and the strong quantum-confined Stark effect [11]–[13]. In the past decade, intensive studies have been performed to enhance the luminescence efficiency and to explore various techniques to improve the LEE, including strain and polarization engineering, surface roughening, patterned substrates and photonic crystals, but with limited success [14]–[18].

Recently, significant progress has been made in the epitaxy and device application of AlGaN nanowire heterostructures [19]–[24]. Due to the efficient strain relaxation, nearly defect-free AlN and AlGaN nanowires can be achieved on Si, sapphire, metal template and other foreign substrates [20], [25]–[27]. These wide bandgap nanostructures can exhibit relatively high luminescence efficiency and efficient current injection at room-temperature [28], [29]. Recent studies on GaN-based nanowires have shown, both theoretically and experimentally, that the formation of nanowire photonic crystal structures, by precisely controlling the size, spacing and morphology of nanowires through selective area epitaxy, can significantly enhance the luminescence emission intensity and stability [30]. Studies have been performed on enhancing the LEE using AlGaN nanowires, which, however, have been limited to either single nanowires [8], [31], or emission from the lateral surfaces of nanowire ensembles [32]. For practical device application, the efficient extraction of TM polarized photons from the top surface of a relatively large area device is highly desired.

In this work, we have performed detailed studies of the ultimate efficiency limit of high AlN content AlGaN deep UV LEDs with TM polarized emission by using nanowire photonic crystal structures. It is observed that, in a well-designed AlGaN nanowire photonic crystal LED structure, the LEE can, in principle, reach over 90% for TM polarized emission from the device top surface by finite difference time domain (FDTD) simulation, which is due to the efficient diffraction of in-plane TM polarized emission to out-of-plane surface emission at the \( \Gamma \) point. Taken into account practical limitations including the absorptive p-Al(Ga)N contact and the presence of metal contact grid, LEE in the range of 30–40% is also expected. Moreover, due to the Purcell effect, the radiative recombination rate and therefore IQE can be significantly modified in nanowire photonic crystal structures, which can be exploited to further enhance the device efficiency. The critical dependence of LEE on various design parameters, including nanowire height, nanowire diameter, variations in the emission wavelengths, and spectral linewidths are studied. Strategies for achieving maximum EQE for given material quality have also been identified. Our calculation shows that the proposed nanowire photonic crystal LED structures are robust and experimentally feasible. The present study reveals the extraordinary potential of AlGaN nanowire photonic crystals for achieving high efficiency deep UV light emitters, which has the potential to provide a paradigm shift for deep UV optoelectronics.

2. Simulation Details

Schematically shown in Fig. 1(a), the LED heterostructure consists of n-type Al(Ga)N nanowire template, n-type AlGaN cladding layer, undoped AlGaN active region with embedded quantum dots/wells, and p-type AlGaN top contact layer. The nanowires are hexagonal in shape and are arranged in a triangular lattice. As shown Fig. 1(b), the lattice constant and diameter of the nanowires are defined as \( a \) and \( d \), and the thicknesses of the AlN and AlGaN segments are \( L_1 \) and \( L_2 \), respectively. The nanowire array is placed above the UV-reflective substrate in a hexagonal area with a side length of 7 \( \mu \)m as shown in Fig. 1(c), and FDTD simulation is performed using the software package Lumerical FDTD Solutions. A UV-reflective substrate with nearly 100% reflectivity can be realized by using AlGaN/AlN distributed Bragg reflectors (DBRs) [33]. The boundary conditions are perfect matched layers (PMLs) set by the software package, which is a standard technique in FDTD simulation to truncate the simulation space without the reflection of outgoing waves back.
to the simulation space [34], [35]. Detailed mathematical description of such boundary conditions can be found in Refs. 34 and 35. A 1 μm distance was left between the photonic structure and any PML as shown in Fig. 1(c). Assuming that the emission is 100% TM polarized, a TM polarized dipole source with central wavelength of \( \sim 239 \) nm is positioned in the active region of only the very center nanowire in the array, which is appropriate for estimating LEE for a large area LED device [36]. The LEE is calculated by integrating the power going upward within a rectangular region above the nanowire array. The area of the rectangular region is sufficiently large to collect the light extracted from the surface. The spectrum of the source is set to have a linewidth (full-width-at-half-maximum (FWHM)) of 50 nm to obtain the broadband response of the photonic structure. The refractive indices of AlGaN and AlN segments are 2.45 and 2.1, respectively [37]. The actual refractive indices, however, may vary depending on the material quality and compositional distribution. The device design, described below, can be readily optimized based on the actual refractive indices. Due to the large bandgap in AlGaN and AlN cladding layers, absorption of emitted light is approximated to be zero.

3. Results and Discussion

Shown in Fig. 2(a) is a typical bandstructure for TM polarization of an AlGaN nanowire photonic crystal structure calculated using the finite-element method simulation package RF module of Comsol Multiphysics. The \( \Gamma \) point is defined as \((0, 0)\) and the M points are defined as \( \pm K_1/2, \pm K_2/2, \) and \( \pm (K_1 - K_2)/2\), where \( K_1 \) and \( K_2 \) are the primitive vectors in the reciprocal space as shown in Fig. 2(b) [38]–[40]. The photonic crystal is beneficial for maximizing LEE near the 4th band \( \Gamma \) point because near the 4th band \( \Gamma \) point the mode profile has even symmetry for the out-of-plane electric field distribution, with the largest overlap with the nanowire center region, shown in the inset of Fig. 2(a), which can efficiently diffract light to the vertical direction [41]. Due to the near-zero in-plane wavevector, the wavevector is mostly pointing out-of-plane, indicating that the TM polarized emission is scattered to vertical surface emission [42]. Since a photonic crystal structure can also change the optical density of states surrounding the active region, the IQE of an LED will be affected by the modified radiative recombination rate under Purcell effect. In this regard, the M point can significantly enhance the IQE because 3 pairs of M points are each coupled by the first order Bragg scattering \((K_1, K_2 \) or \( K_1 - K_2 \) in Fig. 2(b)) forming resonant standing waves in the structure [42], [43]. As both large values of LEE and IQE are critical for achieving high EQE in an
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Fig. 2. (a) The bandstructure for TM polarization of an AlGaN photonic crystal structure calculated using the finite-element method simulation package RF module of Comsol Multiphysics. The lattice constant $a$ is 160 nm and the nanowire diameter $d$ is 95 nm. The inset shows the electric field intensity profile in a unit cell near the 4th band $\Gamma$ point. (b) Schematic for the reciprocal lattice for a hexagonal nanowire array, showing that, due to the near-zero in-plane wavevector, the wavevector is mostly pointing out-of-plane. (c) The calculated LEE for an ideal nanowire photonic crystal structure on a UV-reflective substrate (red dots), and for two realistic cases including: i) on a substrate with nearly zero reflectivity (green triangle), and ii) the presence of absorptive $p$-GaN and metal contact grid (blue diamonds). The calculated result for a conventional planar LED structure is also shown for comparison (black square).

<table>
<thead>
<tr>
<th>$a$ (nm)</th>
<th>$d$ (nm)</th>
<th>LEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>120</td>
<td>63%</td>
</tr>
<tr>
<td>140</td>
<td>110</td>
<td>56%</td>
</tr>
<tr>
<td>160</td>
<td>95</td>
<td>96%</td>
</tr>
</tbody>
</table>

TABLE 1
Calculated Light Extraction Efficiency (LEE) for $\lambda = 239$ nm, $L_1 = 400$ nm and $L_2 = 120$ nm for Three Different Designs of AlGaN Nanowire Photonic Crystal Structures, i.e., Three Different Combinations of ($d$, $a$)

LED, it is necessary to understand how LEE and IQE are affected by the photonic crystal structure and how to use photonic crystal structure to optimize the ultimate EQE.

We first discuss the design of nanowire photonic crystal LED structures on how to maximize LEE for TM polarized photons. Important design parameters include the nanowire diameter ($d$), lattice constant ($a$), and the device layer thicknesses ($L_1$ and $L_2$). The calculation flow chart in identifying the optimum values of $d$, $a$, $L_1$ and $L_2$ is shown in Appendix A. As the $\Gamma$ point can be achieved at the same wavelength with different combinations of nanowire diameters and lattice constants, we firstly varied the nanowire diameter and the lattice constant while keeping $\Gamma$ point at $\lambda = 239$ nm. Three representative combinations of ($d$, $a$) and the corresponding LEE are summarized in Table 1. It is observed that the highest LEE ($\sim 96\%$) is achieved for $d = 95$ nm and $a = 160$ nm. This is attributed to the high out-of-plane coupling constant at this $d/a$ ratio [44]. After optimizing at $a = 160$ nm and $d = 95$ nm using limited three conditions listed in Table 1, the 4th band ($n = 4$ in Fig. 2(a)) $\Gamma$ point is estimated to be 239 nm. Therefore, the subsequent study in this work will be mostly focused on the wavelength at 239 nm. It is important to note that the concept presented in this study can be readily extended to other operating wavelengths. Fig. 2(c) shows the LEE for both planar and nanowire photonic crystal LED structures. The planar film has the same layers and thicknesses as the nanowires. It is evident that LEE is significantly enhanced from $\sim 10\%$ in the planar structure to more than 90% in the photonic crystal structure, which is attributed to the coupling to vertical emission at the 4th $\Gamma$ point. It is therefore evident that operating near the $\Gamma$ point can significantly enhance the LEE. Detailed studies further show that the nanowire height, including variations in
Fig. 3. (a) Variations of LEE with respect to dipole positions. The inset shows the schematic for different
dipole positions in the nanowire structure. The n-AlN segment length ($L_1$) and the total AlGaN segment
length ($L_2$) are kept at 400 nm and 120 nm, respectively. The lattice constant $a$ is 160 nm and the
nanowire diameter $d$ is 95 nm. (b) Variations of the LEE with respect to nanowire diameter for emission
wavelengths at 239 nm with zero linewidth broadening (red square) and with a realistic 15 nm linewidth
broadening (blue dot). The lattice constant $a$ is 160 nm.

$L_1$ and $L_2$ can slightly affect LEE. For example, LEE varies between 81% and 96% as $L_2$ changes
from 80 to 200 nm while keeping $L_1$ at 400 nm (see Appendix B).

In addition, we have performed calculations for two non-ideal cases, including i) zero reflectivity
of the underlying substrate/template, and ii) the presence of absorptive p-GaN and metal contact
grid, which are more representative of real experiments. For Case i), the calculated LEE is in the
range of 40–50%. In Case ii), the p-GaN contact layer has a thickness of 10 nm, and Ni/Au (20 nm
thick) metal contact grid is placed on the device top surface (see Appendix C). LEE over 30% is
calculated at the designed wavelength, shown in Fig. 2(c). The LEE can be further enhanced by
minimizing the thickness of the p-GaN contact layer, and/or by replacing it with a less absorptive
p-AlGaN contact layer. In addition, it is worth mentioning that upon annealing the Ni/Au contact
layer may become partially transparent, which will also enhance the LEE.

In the calculations above, the light source is positioned in the center region of the LED active
region. Experimentally, multiple AlGaN quantum dot/well layers are commonly incorporated in the
device active region. Moreover, depending on the lateral size of the nanowires, quantum dots/wells
may form in the center, or on the lateral semipolar planes of nanowires [21], [45]. Therefore, we
have studied the LEE for a dipole at different positions. Illustrated in the inset of Fig. 3(a), positions 1
to 5 are used to simulate spatial variations along the $z$-axis, while positions 6 to 9 refer to variations
in the $x$-$y$ plane. Shown in Fig. 3(a), it is observed that the LEE stays nearly constant for spatial
variations along the nanowire growth direction (from positions 1 to 5 along the $z$-axis), and exhibits
a small (~5%) reduction for variations along the lateral dimension ($x$-$y$ plane). It is therefore seen
that spatial variations of the quantum dot/well emitters in the device active region has a very small,
or negligible effect on the LEE.

We have further investigated the effect of nanowire diameter variations on the LEE. Shown in
Fig. 3(b) (red squares), the maximum LEE at $\lambda = 239$ nm is obtained for an optimum nanowire
diameter of 95 nm. In the range of 80 nm to 100 nm, LEE still maintains ~85% or higher. Further
increasing nanowire diameters leads to significantly reduced LEE (~70%). This is because the
4th band redshifts with increasing nanowire diameter and, consequently, the operating wavelength
(239 nm) becomes closer to the M point rather than $\Gamma$ point. At or near the M point, the coupling to
vertical emission becomes less efficient, leading to a reduction of LEE. With the use of selective area
epitaxy, it has been demonstrated that variations of the diameter and spacing of AlGaN nanowires
can be controlled to be within ~20 nm [26], [46]–[48]. Therefore, the proposed AlGaN nanowire
photonic crystal LED structure is experimentally feasible. The analysis described above is for a
single wavelength at or near $\Gamma$ point. In practice, due to the homogeneous and inhomogeneous
broadening, spectral linewidths of AlGaN light emitters are generally in the range of 10 to 20 nm.
We have therefore calculated the LEE considering a FWHM of 15 nm, illustrated in Fig. 3(b) (blue
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Fig. 4. Variation of the IQE (a) and EQE (b) for AlGaN nanowire photonic crystal LED structures by changing the nanowire diameter from 80 nm, through 95 nm (Γ point), to 110 nm (M point), while keeping other design parameters identical. Calculations were performed for the intrinsic material IQE ($\eta_{\text{IQE}}$) in the range of 10% to 90%. The peak emission wavelength is at 239 nm with a realistic spectral linewidth $\sim$15 nm. The n-AlN segment length ($L_1$) and the total AlGaN segment length ($L_2$) are kept at 400 nm and 120 nm, respectively. The lattice constant $a$ is 160 nm.

dots). It is seen that the LEE exhibits a negligible change, compared to that of an LED structure with zero linewidth, which means that the LEE remains high though the emission wavelength deviates away from the exact Γ point (See Appendix D). Even considering large variations of the nanowire size, the LEE can, in principle, reach $\sim$75%, or higher for an AlGaN LED device with TM polarized emission.

An additional benefit offered by nanowire photonic crystal LEDs is that the IQE can be enhanced, due to the Purcell effect [49]. We have calculated the Purcell factor for different nanowire photonic crystal designs (see Appendix E) [50]. Variations of the IQE for AlGaN nanowire photonic crystal LEDs are shown in Fig. 4(a) for $\eta_{\text{IQE}}$ in the range of 10% to 90%, where $\eta_{\text{IQE}}$ is the IQE of the LED active region without the presence of photonic crystal structure. The nanowire diameters are varied from 80 nm, through 95 nm (Γ point), to 110 nm (M point), while keeping other design parameters identical. It is seen that significantly enhanced IQE can be expected when operating at, or near the M point. For example, an IQE value of 20% can be enhanced to $\sim$30% when operating at the M point. It is important to note that these analyses are performed based on realistic FWHM $\sim$15 nm. Even larger enhancement of IQE can be expected for emitters with narrower linewidths.

Finally, to achieve high efficiency deep UV light emitters, it is essential to maximize the EQE, i.e., the product of IQE and LEE. Our studies (see Appendix E) suggest that, if the material quality is high with very large IQE ($>90\%$), then the design should be focused on how to enhance the LEE. In this case, the device should operate near the Γ point, with the maximum achievable EQE $>70\%$, indicated by the black arrow in Fig. 4(b). In practice, due to the presence of defects, Auger recombination, and quantum-confined Stark effect, $\eta_{\text{EQE}}$ is relatively low for deep UV LEDs. For devices with a relatively low $\eta_{\text{EQE}}$ of 30%, the IQE can be enhanced to $\sim$44% when operating near the M point, leading to a relatively high EQE of 32%, indicated by the red arrow in Fig. 4(b), which is significantly higher than that ($\sim$12%) when operating at the Γ point and that ($\sim$3%) of conventional planar LEDs.

4. Conclusion

In conclusion, we have investigated the design of AlGaN nanowire photonic crystal LEDs operating in the deep UV wavelength range. It is observed that very large LEE can, in principle, be achieved for TM polarized photons, which was previously not possible for planar quantum well devices. Detailed studies further suggest that the proposed AlGaN nanowire photonic crystal LED structures are robust and experimentally feasible, given the recent advances in the site-controlled epitaxy of...
nanowire heterostructures, and offer rich opportunities to significantly enhance the ultimate EQE of AlGaN deep UV light emitters with both high and low material quality. For example, for AlGaN LEDs with very high material quality, EQE > 70% can be expected by operating near the Γ point of nanowire photonic crystals, whereas for structures with relatively low material quality it is preferred to operate near the M point to enhance the IQE while maintaining reasonably high LEE. The design parameters so far are mostly focused on the Γ point and the M point in the 4th band. By extending the design parameter space, the K point and higher bands could also be utilized to enhance the LED performance, which is now under investigation.

**Appendix A**

**Calculation Flow Chart for Determining d, a, L₁, and L₂**

Fig. 5 shows the flow for determining d, a, L₁, and L₂. First, two-dimensional finite-element method simulation was performed to calculate the bandstructure for different (d, a) combinations and those with Γ point at 239 nm were identified. Then we arbitrarily assigned L₁ to be 400 nm and L₂ to be 100 nm. LEE was then calculated using three-dimensional FDTD simulation and the best (d, a) combination was identified. Using the best (d, a) combination, L₁ and L₂ are optimized again. With the new values for L₁ and L₂, LEE was finally calculated for different (d, a) combinations for comparison.

![Calculation Flow Chart](image)

**Appendix B**

**The Effect of Nanowire Length on the Light Extraction Efficiency (LEE)**

Based on the optimum design described in the main text, we have further calculated the LEE by varying the nanowire height, including L₁ and L₂, while keeping d as 95 nm and a as 160 nm.
Shown in Fig. 6(a), the LEE exhibits negligible variation, in the range of 87% to 94% for different $L_1$ values while keeping $L_2$ at 80 nm and 200 nm, respectively. Similar studies were also performed by varying $L_2$ while keeping $L_1$ at 400 nm. Illustrated in Fig. 6(b), the LEE varies between 81% and 96% as $L_2$ changes from 80 to 200 nm and $L_1$ is kept 400 nm. Though this dependence is not significant, the effect of $L_2$ should be taken into account for optimizing the actual device performance.

**Appendix C**

*Description for the Structure With a p-GaN Layer and Metal Contact Grids*

Compared to the ideal case presented in the manuscript, Case ii) considers more practical experimental conditions, including the incorporation of absorptive p-GaN and metal contact grid. Based on the same nanowire structure shown in Fig. 1(a) in the manuscript, a 10 nm thick p-GaN layer is added on the device top surface, shown in Fig. 7. Metal contact grids consisting of 10 nm Ni and 10 nm Au were then deposited on top of the nanowires. The width of the metal contact grid is 30 nm.

**Appendix D**

*Tolerance for Mismatch between Operation Wavelength and Γ Point*

As shown in Fig. 8, the LEE remains above 80% in a wide wavelength range around 240 nm. As the wavelength decreases from 240 nm to 225 nm, the in-plane wavevector increases to $0.36\pi/a$. 
in the Γ-K direction or \(0.35\pi/a\) in the Γ-M direction. For longer wavelengths between 240 nm and 255 nm, the LEE is also high because of the TM polarization bandgap. As long as the emission spectrum has a reasonably narrow FWHM of around 15–20 nm and the peak wavelength is not far from the Γ point, the overall LEE will remain high. Our design to maximize LEE can tolerate large mismatch between Γ point and the peak wavelength.

Fig. 8. Variation of LEE with wavelength. The lattice constant \(a\) is 160 nm and the diameter \(d\) is 95 nm. The n-AlN segment length \(L_1\) is fixed as 400 nm. The total length \(L_2\) of AlGaN segments is fixed as 120 nm.

Appendix E

Purcell Factor, Internal Quantum Efficiency (IQE), and External Quantum Efficiency (EQE) of AlGaN Nanowire Photonic Crystal Structures

We have calculated the Purcell factor for different nanowire photonic crystal designs by taking the ratio of the actual emitted power in the photonic crystal structure to the emitted power as if in a homogeneous isotropic bulk AlGaN material [50]. Shown in Fig. 9 is the Purcell factor at different wavelengths as the nanowire diameter changes. Depending on the design parameters, a relatively large Purcell factor of \(\sim 5\) can be achieved, which is expected to significantly enhance the IQE.

Fig. 9. Purcell factor for different wavelengths when the diameter is 95 nm and 110 nm. The lattice constant is 160 nm. The n-AlN segment length \(L_1\) is fixed as 400 nm. The total length \(L_2\) of AlGaN segments is fixed as 120 nm.

In order to understand the how IQE and EQE are affected in a photonic crystal structure, we have taken into account the radiative recombination rate modified by the Purcell effect. The radiative recombination rate can be written as,

\[
R'_r(\lambda) = F_p(\lambda)R_r
\]

where \(\lambda\) is the wavelength, \(F_p(\lambda)\) is the Purcell factor, and \(R_r\) is the radiative recombination rate in a homogeneous bulk material without Purcell effect [51]. Note that both the Purcell effect and LEE are wavelength-dependent. We therefore further express IQE as,

\[
\eta_{IQE} = \frac{\int R'_r(\lambda) g(\lambda) \, d\lambda}{\int [R'_r(\lambda) + R_{nr}] g(\lambda) \, d\lambda}
\]
where \( g(\lambda) \) is a Lorentz function approximating a photon distribution with a linewidth \( \Delta \lambda \) at a center wavelength \( \lambda_0 \),

\[
g(\lambda) = \frac{1}{2\pi} \frac{\Delta \lambda}{(\lambda - \lambda_0)^2 + (\Delta \lambda/2)^2}
\]  

(3)

Considering that the IQE of a homogeneous material without Purcell effect being \( \eta_{\text{IQE}} = R_r/(R_r + R_{nr}) \), Eqn. (2) can be written as,

\[
\eta_{\text{IQE}} = \frac{\int F_p(\lambda) g(\lambda) d\lambda}{\int [F_p(\lambda) + 1/\eta_{\text{IQE}} - 1] g(\lambda) d\lambda}
\]  

(4)

It can therefore be seen that the Purcell factor \( F_p(\lambda) \) can modify the IQE in a photonic crystal structure significantly. In order to achieve high efficiency deep UV light emitters, it is essential to maximize the EQE. Taking into account the Purcell effect, the EQE of AlGaN nanowire photonic crystal LEDs can be expressed as,

\[
\eta_{\text{EQE}} = \frac{\int F_p(\lambda)\eta_L(\lambda) g(\lambda) d\lambda}{\int [F_p(\lambda) + 1/\eta_{\text{IQE}} - 1] g(\lambda) d\lambda}
\]  

(5)

where \( \eta_{\text{INJ}} \) is the injection efficiency and \( \eta_L(\lambda) \) is the LEE. It is seen that the optimal design for high efficiency AlGaN nanowire photonic crystal LEDs depends on \( \eta_{\text{IQE}} \), i.e., the material quality.

References


