Non-polar GaInN-Based Light Emitting Diodes:
An Approach for Wavelength-Stable and Polarized-Light Emitters
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ABSTRACT

In absence of piezoelectric polarization along the growth axis, \textit{a}- and \textit{m}-plane green GaInN light emitting diodes
manifest stable emission wavelength -- independent of the injection current density. The shift of the dominant
wavelength is less than 8 nm when varying the forward current density from 0.1 to 38 A/cm$^2$. Furthermore, the light
emitted from the growth surface of such non-polar structures shows a very degree of linear polarization. This is
attributed to a strong valance band splitting in such anisotropically strained wurtzite GaInN quantum wells . Such light
emitting diodes show a high potential for energy efficient display applications.

Keywords: GaN, non-polar, \textit{a}-plane, \textit{m}-plane, light emitting diode,

1. INTRODUCTION

Nowadays, the most efficient light emitters covering deep green and all shorter wavelength portions of the visible
spectrum are typically fabricated by group-III nitride-based heterostructures in particular such with an active layer of
GaN. These single crystalline semiconductors are of wurtzite structure and commonly epitaxially grown along their +c
direction, i.e., having a group-III metal atom in the terminating surface. Due to the uniaxial nature of their structure,
there is a large piezoelectric field acting along the growth direction which can reach a strength of MeV/cm. This is
enough to separate electron and hole wavefunctions inside the thin quantum well (QW). [1-2] In the consequence, the
emission wavelength strongly depends on the actual screening conditions of the QW, which are controlled by the level of
carrier injection and drive current density. This effect is also being considered to limit the device performance of light
emitting diodes (LEDs) in particular in the long-wavelength range of green and deep green. To minimize its influence,
Takeuchi \textit{et al.} proposed the growth of GaN-based light emitter devices on other crystallographic facets. In particular,
suggested to grow structures on \textit{a}- and \textit{m}-planes, for which they predicted the disappearance of the piezoelectric
field.[3] However, early growth experiments including LEDs on such non-polar planes manifested performance
characteristics far below expectations. This was due to poor material quality of the non-polar GaN films grown on a
foreign substrate. Such growth lead to high densities of threading dislocations (10^{10} \text{ cm}^{-2}) as well as a high density of
stacking faults (10^{4} \text{ cm}^{-2}). [4-5] Nevertheless, this approach became viable later, when low-threading-dislocation-density
non-polar and semipolar GaN substrates became available by cutting off such specific plane from a \textit{c}-axis grown bulk
GaN.[6-7] However, for such non-polar growth, emission wavelengths were always limited to the shorter blue
wavelength range (400 – 480 nm). This is due to the fact, that far higher indium incorporation into the QW layer is
required as compared to the same wavelengths in polar \textit{c}-plane growth.

In order to overcome this technological challenge, we have developed an epitaxial process to enable a sufficient large
amount of indium to be embedded in the non-polar QWs. [8-10] In our earlier reports, the growth of a relatively wide
QW with reasonable InN fraction was an essential step to push the emission wavelength beyond 500 nm for both, \textit{a}- and
\textit{m}-plane growth.[8-10] In this paper, we summarize the unique characteristics, in particular the stable emission
wavelength, as well as the polarized emission observed from both, \textit{a}- and \textit{m}-plane LEDs.

2. HOMOEPITAXIAL GROWTH AND CRYSTALLOGRAPHIC QUALITY

A metal organic vapor phase epitaxy (MOVPE) technique with conventional group-III sources of trimethyl gallium,
trimethyl indium, and trimethyl aluminum and a group-V source of NH$_{3}$ was employed for the crystal growth process.
Non-polar $a$- and $m$-plane GaN wafers were prepared from $c$-plane GaN bulk as provided by Kyma Technologies Inc.\cite{11} were used as substrates. Prior to the epitaxial process, these wafers were cleaned to remove possible contaminations and residual chemicals from the manufacturing processes. The growth sequence began with 2-3 $\mu$m thick n-GaN ($[\text{Si}] \sim 3 \times 10^{18} \text{ cm}^{-2}$) to provide lateral conduction. This was necessary due to relatively high resistivity of the substrate wafer. 5 to 10 pairs of 3-4 nm thick GaInN QWs and 20 nm thick GaN barriers were then followed and later capped with a 20 nm thick Mg doped AlGaN electron blocking layer and subsequently 150-200 nm p-GaN ($[\text{Mg}] \sim 5-20 \times 10^{19} \text{ cm}^{-3}$). For contact purposes, a heavily doped 20 nm thick p-GaN ($[\text{Mg}] \sim 1 \times 10^{21} \text{ cm}^{-3}$) was introduced. These layers were typically grown in a single epitaxial process without any interruption.

The morphology of the GaInN/GaN active region observed via atomic force microscopy (AFM) shows striations parallel to the $c$-axis for $a$-plane growth. For the growth on on-axis $m$-plane bulk substrate we find screw dislocation-induced micro faceting\cite{14} of striations that run perpendicular to the $c$-axis and atomic steps along the in-plane $a$-axis. However, the surface roughness of the $m$-plane multiple quantum wells (MQW) is about 0.2-0.3 nm (root mean square (RMS)) as opposed to 1.2-3.3 nm (RMS) for that of the $a$-plane MQWs.\cite{8,12,13} The surface roughness of the $m$-plane MQW is of the same quality as seen in $c$-plane MQWs, i.e., 0.2 – 0.4 nm (RMS).

![Cross-sectional TEM micrographs of 522-nm $a$-plane LEDs on bulk GaN](image)

Figure 1 Cross-sectional TEM micrographs of 522-nm $a$-plane LEDs on bulk GaN (a). No threading dislocation is generated in the active region or homoepitaxial interface along a lateral length of 8 $\mu$m for this $a$-plane green LED (b).\cite{8}

The transmission electron microscope (TEM) analysis reveals that this $a$-plane green LED on bulk GaN contains no visible homoepitaxial boundary and no additional threading dislocations despite of a relative large surface roughness (Figure 1).\cite{8} For this particular sample, the threading dislocation is estimated to be of the order of $10^7 \text{ cm}^{-2}$ or lower. Figure 2 exhibits TEM micrographs from 481 nm (a), 491 nm (b) and 511 nm (c) $m$-plane LEDs. Also there are no homoepitaxial boundaries observed for these types of non-polar LEDs. The 481 nm LED (Figure 1 (a)) is free of any dislocation in the observable area while there are some misfit dislocations generated in the active region of the 491 nm LED (Figure 1 (b)) with a corresponding density in the lower $10^8 \text{ cm}^{-2}$. However, the 511-nm LED contains a high density of misfit dislocations ($\sim 10^{10} \text{ cm}^{-2}$) initiated in the active region (Figure 2 (c)). All misfit dislocations were edge-type.\cite{12} These dislocations are likely to limit the device performance as explained in the following sections.
3. INTERNAL QUANTUM EFFICIENCY

For an estimate of the internal quantum efficiency (IQE), the photoluminescence (PL) intensity at room temperature was compared to that at 4.2 K. In order to maximize photo carrier capture into the QWs, photo excitation was performed at 408 nm in the transparent spectral region of the GaN layers. By minimizing the V-defect density in the MQW active region, our group has achieved an IQE of 40% and 15% at room temperature (RT) for 530 and 555 nm c-plane LEDs, respectively. These values can be extrapolated to 18% and 8% for each device when operated at 50 A/cm².[15] Recent reports claim IQE values of 75% at 50 A/cm² for 440 nm blue c-plane LEDs and 40% at 50A/cm² for 540 nm green c-plane LEDs.[16] In case of a-plane 511 nm green LEDs, we have achieved an IQE of 25% at RT. To the best of our knowledge, this value is the highest value reported for this particular non-polar plane.

For m-plane MQW samples, PL properties at RT are summarized in Figure 3. All samples show single-peak emission. From 480 nm to 520 nm, the spectral PL power intensity drops by one order of magnitude (Figure 3 (a)). Across the same spectral range, the line width of the emission peak is around 25-35 nm (full width at half maximum (FWHM)) with a broadening trend as PL wavelength increases (Figure 3 (b)). Under the common assumption of negligible non-radiative recombination at low temperature, we derive upper values of IQE (Figure 3 (c)). In the 450 nm MQW sample, we find a very high value of 67% at RT. This value proves that the blue m-plane MQW is of the same quality as achieved in c-plane material. For longer emission wavelength, these values, however, drop to 35% at 478 nm and 8% at 500 nm. The rapid decrease in IQE is likely to reflect the crystallographic quality of the GaInN QW layer. That layer shows an increasing density of misfit dislocation as described in Section 2.
4. WAVELENGTH-STABLE LED

EL spectra of blue-green and green m-axis LEDs driven at 12.6 A/cm² are summarized in Figure 4. Their EL spectrum line widths are around 29-34 nm (155 – 165 meV). These LEDs were driven up to 30 A/cm². The 489 nm, 494 nm, and 511 nm LEDs (sample G, H and I) reach maximum-partial light output power (LOP) of 4.5 mW, 1.3 mW, and 0.2 mW, respectively. With further optimization of the MQW epitaxial growth process, LOP has now been improved to 0.4 mW at 511 nm (sample J). LOP of a 490 nm LED, as measured on bare fabricated but unencapsulated (350 µm)² dies through the substrate manifests comparable achievement levels of several mW at 35 A/cm². However, there is a roll-off of LOP stretching over nearly two orders of magnitude as the emission wavelength extends from 480 nm to 510 nm. A similar trend has also been observed in the IQE of the active region (Figure 3 (c)). As shown in Figure 2 (c), the structural quality of the GaInN/GaN active layers analyzed by TEM tentatively suggests that these efficiency losses can be attributed to an increasing density of defects in the longer-wavelength LEDs. Further epitaxial process development should allow us to solve such issues.

In order to investigate the degree of piezoelectric polarization effect on the GaInN QW, we analyzed the injection current dependence of EL spectra for a-plane and m-plane green LEDs. Examples of these spectra are plotted in Figure 5. Here we are considering the shift of the peak wavelength as an indicator for the screening effect of injected carriers over the piezoelectric field. In a polar c-plane green LED, it is common to see a blue shift of its peak wavelength with increasing injection current density. However, the emission peak wavelengths of both non-polar green LEDs remain quite constant across the whole current range. These results suggest that such polarization effect can be avoided by growing an LED on these non-polar planes. More experimental results of peak wavelength shift for polar and non-polar near-UV to green LEDs are summarized in Figure 6. For c-plane LEDs (peak wavelength 418 – 535 nm at 12.6 A/cm²), a small wavelength shift less than 5 nm can be seen when the peak wavelength is below 470 nm. Such blue shift is then gradually increased as the wavelength gets longer (Figure 6 (a)). Most of c-plane LEDs suffer a large wavelength drift...
Figure 4. EL spectra of cyan and green m-plane LEDs (a) and their corresponding LOP (b). F-J are the sample IDs. The QW thickness along with estimated InN molar fraction are presented next to each plot in (b).[12]

Figure 5. EL spectra of a-plane (a) and m-plane LEDs (b) at various injection current densities. Well-defined single peak emission was seen for both types of non-polar LEDs. The linewidth of m-plane one (162 meV) is relatively smaller than those of a-plane one (177 meV) and c-plane one (182 meV, data not shown). [13]
over 20 nm when driving an injection current from 0.1 to 10 A/cm². For a-plane LEDs, such drift is smaller than 5 nm even for the green light emission (Figure 6 (b)). The similar property can also be observed for the m-plane LEDs. For m-plane cyan and green LED, the shift is as small as 3 nm when varying the injection current from 0.1 to 30 A/cm² (Figure 6 (c)). It is commonly expected that in order to get the non-polar LEDs to emit in these wavelength ranges, it requires GaInN QW with more InN fraction than c-plane LEDs emitting the same wavelength at the same typical injection current. For polar structure, this high InN fraction QW simply implies as an even larger piezoelectric polarization effect. However, it is not the case for these non-polar LEDs.

In terms of human color perception, we compare the chromaticity coordinates of these three different types of cyan and green LEDs in Figure 7. For c-plane LEDs, there exists a significant change of CIE-X and Y coordinates as a function of injection current density in the CIE space map (Figure 7 (a)). This large variation would require active color management if this type of polar LEDs should be integrated into any high quality light source. On the other hand, any color change is significantly less for both, a-plane and m-plane LEDs (Figure 7 (b)). This aspect is a highly beneficial property of these non-polar LEDs in any application in which color stability is necessary.
Figure 7. Current dependence of the plots are evaluated from the same set of cyan and green LEDs shown in Figure 6. Circles and squares represent the CIE 1931 coordinates for non-polar a-plane LEDs and m-plane LEDs, respectively. Arrows indicate the direction with increasing injection current density. The theoretical loci of emitters with a 100% saturation are labeled in blue.

5. NON-POLAR LED AS A POLARIZED LIGHT EMITTER

The valence band maximum in wurtzite GaN has symmetries of $\Gamma_7 \vert x + iy \rangle$-like heavy hole (HH), $\Gamma_7 \vert x - iy \rangle$-like light hole (LH), and $\Gamma_7 \vert z \rangle$-like crystal field split-off hole (CH), in order of decreasing electron energy. We define Cartesian coordinates $x$, $y$, and $z$ along the $a$-, $m$- and $c$-axis, respectively. Transitions between the $\Gamma_7$ electron state and both, the $\Gamma_9$ (HH) and $\Gamma_7$ (LH) states are permitted for $E // c$, while the transition to $\Gamma_7$ (CH) is allowed for $E \perp c$, where $E$ is the electric field vector of dipole radiation. For pseudomorphically strained $c$-plane GaInN/GaN QWs, due to the isotropic biaxial strain within the QW plane, the $\vert x\rangle$ and $\vert y\rangle$ states of HH and LH remain degenerate and light emission involving $E \perp c$ propagating along the $c$-axis becomes unpolarized.[22]

For nonpolar GaInN/GaN heterostructures where the crystal $c$-axis lies within the QW plane, large anisotropic strain in the $x$-$z$ plane breaks the symmetry in the $x$-$y$ plane. This splits the $\vert x \pm iy \rangle$-states into $\vert x \rangle$ and $\vert y \rangle$ states. For $m$-plane QWs, the valence bands are reconstructed in the order of $\vert x \rangle$, $\vert y \rangle$, and $\vert z \rangle$ with decreasing energy. Recombination prefers the lower-energy transition between $\Gamma_7$ electrons and $\vert z \rangle$-like holes, resulting in a high degree of $a$-axis-polarized light emission from the $m$-plane epitaxial surface. On the other hand, for $a$-plane QWs, a similar high degree of $m$-axis polarized light emission is expected.[22]

The degree of light polarization can be expressed in terms of the polarization ratio ($\rho$) as follows.

$$\rho = \frac{l_{\text{max}} - l_{\text{max}}(90^\circ)}{l_{\text{max}} + l_{\text{max}}(90^\circ)}$$

where $l_{\text{max}}$ is the maximum light intensity when measured through a rotated linear polarizer, and $l_{\text{max}}(90^\circ)$ is the component normal to the direction of maximum light intensity. Polarized 472 nm blue LEDs in $m$-plane QWs reaching $\rho = 0.86$ in EL have been reported by Masui et al.[17] In the PL of $m$-plane QWs, Kubota et al.[18] obtained $\rho = 0.7$ at 430 nm and found that $\rho$ increased with wavelength to $\rho = 0.9$ at 485 nm. Fellows et al. reported $\rho = 0.53$ in EL from semipolar (1122) plane QWs on GaN in a 570 nm yellow LED (see Figure 8).[19] Kyono et al. obtained $\rho = 0.2$ to 0.3 from 400 to 550 nm in EL in semipolar (2021) LEDs.[21] In this section, we report on the polarized light emission in $m$-plane and $a$-plane GaInN/GaN MQW structures with peak emission wavelength from 400 nm to 515 nm.
Figure 7. Polarization-resolved PL spectra of $a$- and $m$-plane MQW samples. Polarizer configurations together with the PL peak wavelengths are included for each polarized spectrum. [22]

Figure 8. Polarization ratios of $a$- and $m$-plane MQW samples as a function of PL peak wavelength. The InN fraction and well width are included for two 485 nm samples.[22] Reference data are provided for comparison with data from Fellows et al. [19] and Chiu et al. [20] are of EL peak wavelength.

Figure 8. Polarization ratios of $a$- and $m$-plane MQW samples as a function of PL peak wavelength. The InN fraction and well width are included for two 485 nm samples.[22] Reference data are provided for comparison with data from Fellows et al. [19] and Chiu et al. [20] are of EL peak wavelength.
We observed maximum PL intensity from \(a\)-plane MQW when \(E\) was parallel to the in-plane \(m\)-axis (Figure 7(a)), while
the minimum intensity was confirmed under \(E//c\)-axis configuration. For this \(a\)-plane green MQW sample, we found
that \(\rho = 0.59\). For \(m\)-plane MQWs (Figure 7(b)), the maximum PL intensity was observed at \(E//a\)-axis while the
minimum one was of \(E//c\)-axis configuration. The polarization ratio of 0.89 was estimated for this \(m\)-plane green
MQW.\[22\]
The polarization ratio was obtained in PL at RT for a series of \(m\)-plane and \(a\)-plane MQW structures with peak emission
wavelength in the range of 400 nm to 515 nm as summarized in Figure 8. In the \(m\)-plane MQWs the polarization ratio
increases with peak emission wavelength. The same is seen in the \(a\)-plane structures but with lower values of
polarization ratio and a slower increase. According to Kojima et al., the valence band splitting is dominated by InN
fraction \((x)\) and, to a lesser extent, QW thickness \((L_z)\).\[23\] The in-plane anisotropic strain of non-polar QWs increases as
more indium is incorporated in the QW to extend its emission wavelength. This further splits the valence bands and,
thus, offers a higher probability for recombination through the upper state in the valence band. The result is a higher \(\rho\)
with longer emission wavelength. Our experimental results agree with the theoretical study.
Also, higher \(\rho\) is observed for \(m\)-plane MQWs over the \(a\)-plane ones. However, current theory expects the same
amplitude of splitting for both, \(a\)- and \(m\)-plane MQWs. This discrepancy could possibly be explained by a relaxation of
polarization through surface roughness. In the \(a\)-plane structures we find higher roughness values than in the \(m\)-plane
ones (see section 2).\[22\]
The high degree of linear polarization is still preserved in EL operation of the respective LEDs. The transversal
polarization in the far-field EL emission propagating along the \(m\)-axis of the 505 nm green \(m\)-plane Ga\(_{x}\)In\(_{1-x}\)N/GaN
\((x = 0.18, L_z = 3.9\) nm) LED has been analyzed (Figure 9). Spectra are found to be composed of two components
polarized parallel to the \(a\)- and \(c\)-axes, respectively. The former spectrum has a single peak at 505 nm, while the latter
has a peak at 491 nm with 13% of the intensity of the peak at 505 nm (Figure 9(a)). The separation between these two
peaks is approximately 70 meV and the relative intensities suggest a splitting of the valence band states involved. The
angular dependence of the polarized EL intensity out of the \(m\)-plane is shown in Figure 9(b). The data can be fitted by
the assumption of two independent linear polarization components as follows:
\[
I_\theta = I_{//c} \cos^2 \theta + I_{//a} \sin^2 \theta,
\]
where \(I_\theta\) is the intensity of light at polarization angle \(\theta\) while \(I_{//c}\) and \(I_{//a}\) are the intensity of polarized light along the \(a\)-
and \(c\)-axes, respectively. As shown by in Figure 9(b), the interpolation line well fits the measurement results. This
indicates a very low component of arbitrary polarization, such as in the result of light scattering within the LED die. The
polarization ratio \(\rho\) is estimated to be 0.77.\[22\]

For the application for backlighting units in liquid crystal display (LCD) modulators, the quantitative spectra of green \(m\)-
and \(c\)-plane LEDs with and without linear polarizer have been analyzed (Figure 10). While propagation through the
linear polarizer reduces the light output in the \(c\)-plane LED by 57.7% (Figure 10(a)), for the \(m\)-plane LED the
 corresponding loss is only 25.4% (Figure 10(b)). This results in a higher overall system efficiency enhancement factor \(\zeta = 1+1/\rho\).
For our case of \(\rho = 0.77\), one can obtain the same power of linearly polarized light with \(1/\zeta = 44\%\) less source
light power. The approach therefore becomes competitive as soon as the linearly polarized green LED reaches an
efficiency of \(1/(1+\rho)\) of that of the competing unpolarized light source. Therefore, note that an \(m\)-plane LED needs to be
only 50% as efficient as that of a \(c\)-plane one in the perfect case \((\rho = 1)\). The current achievement via this \(m\)-plane LED
is considered a significant step closer to this ideal case.\[22\]
Figure 9. Polarization resolved EL spectra of m-plane LED (a) and EL intensity as a function of polarization angle. At 0 and 180°, the polarizer is parallel the c-axis, and at 90° it is parallel to the in-plane a-axis.[22]

Figure 10. EL spectra comparison for c-plane LED with and without polarizer (a) and similar comparison for m-plane LED (b).[22]
CONCLUSIONS

Non-polar $a$- and $m$-plane GaInN QWs have been proposed and explored as an alternative choice for highly efficient LEDs. In absence of piezoelectric polarization such structures have the potential of higher efficiency in the radiative recombination in the GaInN QW compared to the common $c$-plane LED. This benefit should be particularly important for green light emission. Under variation of the injection current from 0.1 to 38 A/cm², we observe only a minimal blue shift of the wavelength by less than 8 nm for $a$-plane and less than 3 nm for $m$-plane green LEDs. This is a significant improvement over the 24 nm seen in typical 510 nm $c$-plane LEDs. This unique aspect significantly simplifies color management for a white-light source with multiple color LEDs.

The uniaxial nature of the wurtzite material systems allows for anisotropic strain splitting of the valence band of QWs grown along the $a$- and $m$-axes. This leads to a strong modification of the selection rules for interband emission allowing a high degree of linearly polarized light to be emitted through the top growth surface. Our $m$-plane GaInN/GaN MQWs structures reach a polarization ratio of $\rho = 0.7$ at 460 nm and this value grows to $\rho = 0.9$ at 515 nm peak wavelength. For $a$-plane structures, we always find lower values of $\rho$ at 480 nm – 510 nm. Deploying $m$-plane LEDs with such a high degree of polarization should result in significant power savings for LCD displays technologies.

ACKNOWLEDGEMENT

We would like to acknowledge E.A. Preble, T. Paskova, and D. Hanser (currently with SRI international Inc.) at Kyma Technologies for providing bulk GaN substrates of different crystal orientations. This work was supported by DOE/NExT Solid-State Lighting Contracts of Directed Research under DE-EE0000627. This work on polarization-light emitters was supported by the National Science Foundation (NSF) Smart Lighting Engineering Research Center (# EEC-0812056).

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